Appendix 12
Gasification By-Products Information

- DOE Report On Utilization Of Coal Gasification Slags
- U.S. Geological Survey Information On Sulfur Market

DOE Report On Utilization Of Coal Gasification Slags

Utilization of Lightweight Materials Made from Coal Gasification Slags

Cooperative Agreement No. DE-FC21-94MC30056

Final Technical Report

December 2000

Principal Authors:
Vas Choudhry
Stephen Kwan
Steven R. Hadley

Prepared for:

U.S. Department of Energy
Office of Fossil Energy
National Energy Technology Laboratory
Morgantown, West Virginia

Prepared by:

Praxis Engineers, Inc.
852 North Hillview Drive
Milpitas, California 95035
Tel. No: (408) 945-4282
Fax No: (408) 263-2821

With input from:
Fuller Company
Pennsylvania State University
Harvey Cement Products, Inc.
Silbrico Company, Inc.

Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Available to the public from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161; phone orders accepted at (703) 487-4650.

Acknowledgments

The authors would like to acknowledge the contributions of the late Sidney M. Cohen in his capacity as Director of Research and Development at Fuller Company. A pioneer in the development of lightweight aggregates from clay and shale materials, he became an early supporter of expanded slag, and devoted much personal time to developing economic, commercial-scale techniques for slag expansion. Without his interest and support the project would not have achieved its goals. He passed the torch to Michael Prokesch, who continued to make valuable contributions to the project at Fuller.

We also appreciate the tireless work and encouragement of Thomas Zimmerle at Silbrico in the effort to make ultra-lightweight aggregates from slag. We recognize the efforts of Phil and Skip Steck at Harvey Cement Products, who applied their years of experience in making blocks to expanded slag aggregates. They went the extra mile in helping the project by producing expanded slag blocks at the plant.

Praxis acknowledges the contributions of the organizations that participated in the project and provided cost sharing. In particular, we recognize the efforts of the lead contact persons at these organizations. They include Nandor Hertz and Michael Epstein at the Electric Power Research Institute (EPRI) and Dan Banerjee at the Illinois Clean Coal Institute (ICCI). We appreciate the constructive input from the project managers at DOE, especially Scott Renninger, who helped keep the project focused on the main goals.

Abstract

The objective of the project entitled "Utilization of Lightweight Materials Made from Coal Gasification Slags" was to demonstrate the technical and economic viability of manufacturing low-unit-weight products from coal gasification slags which can be used as substitutes for conventional lightweight and ultra-lightweight aggregates. In Phase I, the technology developed by Praxis to produce lightweight aggregates from slag was applied to produce a large batch (10 tons) of expanded slag (termed SLA), using pilot direct-fired rotary kilns and a fluidized bed calciner. The expanded products were evaluated using basic characterization and application-oriented tests. Phase II involved the demonstration and evaluation of the use of expanded slag aggregates to produce a number of end-use applications including lightweight roof tiles, lightweight precast products (e.g., masonry blocks), structural concrete, insulating concrete, loose fill insulation, and as a substitute for expanded perlite and vermiculite in horticultural applications. Prototypes of these end-use applications were made and tested with the assistance of commercial manufacturers. Finally, the economics of expanded slag production was determined and compared with the alternative of slag disposal. Production of value-added products from SLA has a significant potential to enhance the overall gasification process economics, especially when the avoided costs of disposal are considered.

Keywords: slag, expanded slag, coal gasification slag, lightweight aggregates, gasification by-product utilization, waste utilization.

TABLE OF CONTENTS

EXECUTIVE SUMMARY I

1.0 INTRODUCTION, OBJECTIVES, SCOPE, AND METHODOLOGY 1

1.1 Overview and Background Information 1
1.2 Phase II Project Objectives 4
1.3 Scope of Phase II Work 4
Task 2.1 Test Plan for Applications of Expanded Slags (Field Studies) 4
Task 2.2 Field Studies to Test Expanded Slag Utilization 5
Task 2.3 Data Analysis of Commercial Utilization of Expanded Slags 5
Task 2.4 Economic Analysis of Expanded Slag Utilization 5
Task 2.5 Separation of Char from Slag for Tampa Electric Company IGCC Plant 5
Task 2.6 Testing of Slag as Raw Material Additive in Portland Cement Kiln Feed 5
Task 2.7 Utilization of Slag as Raw Material in Portland Cement (Pilot Testing) 6
Task 3.0 Final Report 6
1.4 Project Methodology 6
1.5 Phase I Work Summary 7
1.5.1 Slag Processing for Char Removal 7
1.5.2 SLA Production Using a Direct-fired Rotary Kiln 7
1.5.3 SLA Production Using a Fluidized Bed Expander 8

2.0 RESULTS AND DISCUSSION OF PHASE II WORK 10

2.1 Test Plan for Applications Testing of Expanded Slags (Field Studies) (Task 2.1) 10
2.2 Field Studies to Test Expanded Slag Utilization (Task 2.2) 11
2.3 Data Analysis of Commercial Utilization of Expanded Slags (Task 2.3) 11
2.3.1 Laboratory Evaluation of SLA for Roof Tile Application 12
2.3.2. Lightweight Masonry Blocks (CMUs) 19
2.3.3 Laboratory Evaluation of SLA for Structural Concrete Application 27
2.3.4 Laboratory Evaluation of SLA for Insulating Concrete Application 34
2.3.5 Laboratory Evaluation of SLA for Loose Fill Insulation Application 35
2.3.6 Laboratory Evaluation of SLA in Horticultural Applications 36
2.3.7 Evaluation of SLA in Production of Cement Panels (Waterproof Boards) 38
2.4 Economic Analysis Of Expanded Slag Production And Utilization (Task 2.4) 39
2.4.1 Costs of Production of LWA and ULWA Made from Expanded Slag 41
2.4.2 Market Assessment of Conventional LWA and SLA 44
2.4.3 Solid Waste Management Costs 47
2.4.4 Economic Evaluation of SLA Production 47
2.5 Separation of Char from Slag from Tampa Electric IGCC Plant (Task 2.5) 49
2.5.1 Laboratory Testing of TEC Slag for Char Removal 50
2.5.2 Development of Conceptual Design for a Char Separation Facility 52
2.5.3 TEC Clean Slag Production Economics 53
2.5.4 Conduct Applications-Oriented Testing of TEC Slag 54
2.5.5 Utilization of Slag/Char Separation Process at DOE-Funded IGCC Plants 55
2.5.6 Conclusions 56

2.6 Laboratory Studies of Slag as Raw Material in Portland Cement Kiln Feed (Task 2.6)......56
2.6.1 Summary of Laboratory Tests......66
2.7 Pilot Studies on Slag as Raw Material in Portland Cement Kiln Feed (Task 2.7)......66
2.8 Pozzolonic Activity of Prepared Gasifier Slag......76
3.0 FINAL AND OTHER REPORTS......80
4.0 CONCLUSIONS AND RECOMMENDATIONS......81
4.1 General Conclusions......81
4.2 Specific Conclusions from Applications Testing......82
4.2.1 Lightweight Aggregate Applications......82
4.2.2 Ultra-lightweight Aggregate Applications......83
4.3 Economics of SLA Production......84
4.4 Recommendations for Future Work......85
LIST OF ACRONYMS AND ABBREVIATIONS......86
APPENDIX A. TEST PLAN FOR APPLICATIONS OF EXPANDED SLAGS (TASK 2.1)......1

LIST OF TABLES

Table 1. Cement Levels to Test SLA I as Structural Aggregate....12
Table 2. Formulations and 7-Day Compressive Strength of Roof Tile Samples....13
Table 3. 28-Day Compressive Strength Results for Roof Tile Application....15
Table 4. Evaluation of SLA III as Aggregate in Roof Tile Application....16
Table 5. 28-Day Strength Results of SLA in Roof Tile Application....17
Table 6. Size Gradation of Aggregate Mix Used in Roof Tile Tests....18
Table 7. Evaluation of SLA III as Aggregate in Roof Tile Application....19
Table 8. Size Distribution of Aggregates Used for Concrete Block Application....20
Table 9. LWA and Cement Concrete Requirements for CMU Applications....21
Table 10. Results of Batch Mix Tests Conducted for Masonry Blocks Using SLA....22
Table 11. Results of Batch Mix Tests for Masonry Blocks Using SLA (2)....23
Table 12. Results of Batch Mix Tests for Masonry Blocks Using SLA III....24
Table 13. Additional Results of Batch Mix Tests for Masonry Blocks Using SLA....25
Table 14. Mix Proportions for Production Batch of Lightweight Blocks....26
Table 15. Compressive Strength and Unit Weight Test Results for Lightweight Blocks....26
Table 16. Summary of Test Results for Use of SLA in Lightweight Block Application....27
Table 17. Cement Levels Used in Testing SLA as Structural Aggregate....27
Table 18. LWA and Concrete Unit Weight and Strength Requirements....28
Table 19. Samples of Materials Used for Structural Aggregate Testing....28
Table 20. Size Distribution of LWA Materials and Sand Used in Structural Concrete....29
Table 21. Expanded SLA Products Tested and Cement Levels Used....29
Table 22. Use of SLA for Structural Lightweight Concrete Without Sand....31
Table 23. Evaluation of SLAs for Sand-Lightweight Concrete Application....32
Table 24. Resistance of Concrete to Rapid Freeze/Thaw (ASTM C 666, Procedure B)....34
Table 25. Apparent Thermal Conductivity and Thermal Resistance of SLA Test Specimens....35
Table 26. Thermal Conductivity and Thermal Resistance of SLA for Loose Fill Insulation....36
Table 27. Evaluation of Expanded Slag in Supporting Plant Growth....37
Table 28. Mix Design and Modulus of Rupture Test Results for SLA in Panel Application....39
Table 29. Design Criteria for Plant to Process Gasifier Slag....41
Table 30. Fuel Requirements for Various Case Studies....42
Table 31. Comparative Costs of Kiln Production of LWA vs. SLA....43
Table 32. Comparative Costs of Producing ULWA vs. SLA....44
Table 33. U.S. Production of Expanded Shales, Clays, and Volcanic LWAs....45
Table 34. U.S. Production of Perlite and Vermiculite....46
Table 35. Typical Regional Prices of Lightweight Aggregates....46
Table 36. Estimated Market Prices for LWAs, ULWAs, and SLA by Application....47
Table 37. Economic Analysis Summary....49
Table 38. Results of Char Separation for TEC Slag....51
Table 39. Slag/Char Separation Results from Process Steps 1 & 2 for Various Slags....52
Table 40. Slag Char Separation Costs and Economics Summary....54
Table 41. Utilization of Char-Free TEC Slag as Aggregate in Cement Concrete....55
Table 42. Utilization of TEC Slag as Feedstock for LWA Production....55
Table 43. Calculated Cement Clinker Chemistry (Pre-Blended Raw Meal, 0% Slag)....68
Table 44. Calculated Cement Clinker Chemistry (Pre-Blended Raw Meal, 3% Slag)....69
Table 45. Calculated Cement Clinker Chemistry (Pre-Blended Raw Meal, 5% Slag)....70

Table 46. Calculated Cement Clinker Chemistry (Pre-Blended Raw Meal, 10% Slag)................71
Table 47. Summary of Free Lime Tests Using Pre-Blended Cement Kiln Raw Meal..................71
Table 48. Calculated Cement Clinker Chemistry (Component Raw Ingredients, 0% Slag) 72
Table 49. Calculated Cement Clinker Chemistry (Component Raw Ingredients, 3% Slag) 73
Table 50. Calculated Cement Clinker Chemistry (Component Raw Ingredients, 5% Slag) 74
Table 51. Calculated Cement Clinker Chemistry (Component Raw Ingredients, 8.5% Slag) 75
Table 52. Summary of Free Lime Test Using Raw Ingredients 75
Table 53. Summary of Free Lime Test Using Raw Ingredients with Lower Silica Modulus 75
Table 54. ASTM C 311 Results Using Specially Prepared Slag..76
Table 55. ASTM C 593 Results Using Specially Prepared Slag..77
Table 56. Initial Particle Size Distribution of Slag Prior to Bond Ball Mill Grindability Test.....77
Table 57. Slag Bond Ball Mill Grindability Test Results...78
Table 58. Sedigraph Particle Size Distribution of Ground Slag...78
Table 59. ASTM C 311 Results Using -200 Mesh Ball Milled Slag..79
Table 60. ASTM C 593 Results Using -200 Mesh Ball Milled Slag..79

LIST OF FIGURES

Figure 1. Slag Utilization Applications 2
Figure 2. X-ray Diffraction Pattern of Raw Kiln Feed (5-65° 2?, 2°/min)...................................59
Figure 3. TGA Weight Loss Curve of Raw Kiln Feed (122-1892°F (50-1050°C), 10°C/min).....59
Figure 4. X-ray Diffraction Pattern of Clinker Formed at 2012°F (1100°C) (5-65° 2?, 2°/min)..61
Figure 5. X-ray Diffraction Pattern of Clinker Formed at 2192°F (1200°C) (5-65° 2?, 2°/min)..61
Figure 6. X-ray Diffraction Pattern of Clinker Formed at 2372°F (1300°C) (5-65° 2?, 2°/min)..62
Figure 7. X-ray Diffraction Pattern of Clinker Formed at 2642°F (1450°C) (5-65° 2?, 2°/min)..62
Figure 8. X-ray Diffraction Pattern of Raw Kiln Feed with 5% Ground Slag (5-65° 2?, 2°/min)63
Figure 9. X-ray Diffraction Pattern of Raw Kiln Feed with 10% Ground Slag 64
Figure 10. Isothermal Calorimetry of Clinkers Formed at Various Temperatures........................65
Figure 11. X-Ray Diffraction Analysis of Clinkers Formed at Various Temperatures.................66

EXECUTIVE SUMMARY

The major objectives of the project, entitled "Utilization of Lightweight Materials Made from Coal Gasification Slags," were to demonstrate the technical and economic viability of commercial production of lightweight aggregates (LWA) and ultra-lightweight aggregates (ULWA) from slag and to test the suitability of these aggregates for various applications. LWAs are typically produced by thermal expansion or pyroprocessing of expansive shales and clays, while ULWAs are produced by pyroprocessing of perlite or vermiculite ores. While LWAs and ULWAs tend to be used in relatively low-volume applications, they command fairly high prices relative to normal-weight aggregates. It was envisaged that the development of a balanced mix of low-, medium-, and high-value applications for slag lightweight aggregates (SLA) would not only ensure total utilization of slag, but may even generate a revenue stream for integrated-gasification combined-cycle (IGCC) facilities while eliminating disposal costs.

Primary funding for the project was provided by DOE's National Energy Technology Laboratory (NETL) at Morgantown, with significant cost sharing by the Electric Power Research Institute (EPRI) and Illinois Clean Coal Institute (ICCI). In addition, several industry participants, including Fuller Company, Harvey Cement Products, Inc., and Silbrico, Inc. provided significant in-kind cost sharing.

The project team consisted of Praxis Engineers, Inc. as the prime contractor, with significant participation from Fuller Company's R&D Division, as well as Harvey Cement Products and Silbrico.

The project goals were accomplished in two phases. Phase I comprised the separation and recovery of char (unconverted carbon) from the slag, and production of LWA and ULWA from slag at the large pilot scale. A 20-ton sample of slag (the primary slag) was collected from one source, and additional samples of another slag were subsequently obtained for confirmatory testing of the processing steps. A third slag was later added to the project within the same budget, based on the interest shown in the technology by an IGCC gasifier operator. The slag samples used in the program were generated from two different gasification processes, namely, those used by Destec and Texaco, using different bituminous coals. Thus the char separation and expanded slag production processes demonstrated during the project can be generalized to apply to most of the coals or gasification processes in current application in the United States, including the Tampa Electric and Wabash River Repowering IGCC projects co-funded by DOE.

Since the char present in gasification slag constitutes a hindrance to its utilization, its removal is a critical step in the development of utilization applications for slag. Separation and recovery of char from slag using the process developed by Praxis Engineers, Inc. was demonstrated successfully under this program using a 400-lb/hour pilot plant.

The char separation step was followed by successful demonstration of the production of LWA and ULWA from slag at the pilot scale, using technology developed by Praxis. Two sizes of rotary kilns and a fluidized bed expander were set up at the facilities of Fuller Company, a leading manufacturer of kiln equipment for the LWA industry, and used to pyroprocess the project slags to produce large quantities of expanded slag aggregates of various size gradations and with unit weights ranging from 16 to 50 lb/ft^3. All of the project slag samples tested expanded at temperatures ~400°F lower than those required for pyroprocessing of expansive shales and clays. This represents significant savings in pyroprocessing fuel energy requirements. In all three expansion processes that were demonstrated, sufficient control of the product unit weight as a function of temperature was possible to produce LWAs and ULWAs.

In Phase II, the SLA products were first tested at the laboratory scale for their suitability as replacements for LWAs in the manufacture of precast concrete products (e.g., masonry blocks and roof tiles), lightweight structural concrete, and concrete panels. They were also tested for their suitability as replacements for ULWAs in the manufacture of insulating concrete, loose fill insulation and in horticultural applications. Subsequently some of these applications were tested at a larger scale with the involvement of commercial manufacturing plants, using ASTM and industry test methods to evaluate the products. The major findings for these applications are summarized below.

Lightweight Blocks. SLA aggregates were successfully tested for production of lightweight blocks or concrete masonry units (CMU). The target lightweight block product (8" CMU) weighs <27 lb on a dry basis. The ASTM and industry requirements for concrete used for this application include a compressive strength of 2,000 psi at a unit weight of <105lb/ft^3, using a typical cement-to-aggregate ratio of <1:5. Following laboratory development work, 250 blocks were produced using a mix incorporating 40% SLA (by weight) and a cement-to-aggregate ratio of 1:6. In the production of SLA blocks, the entire automated production and post-production manufacturing process was used without modification. They were handled through the mechanized processing steps without any problems, and no special curing or handling was needed. The product met both industry and ASTM requirements.

Structural Concrete. SLA was also successfully used to make structural concrete that met ASTM and industry requirements of compressive strengths of 2,500-4,000 psi for sand LWA concrete with unit weights in the 105-115 lb/ft^3 range, using a typical industry cement-to-aggregate ratio of 1:4. Concrete made from a combination of SLA and conventional clay-based LWA had an even higher strength of 5,500 psi.

Concrete Panels. Concrete panels (cement boards) are used for structural reinforcement and as water-resistant backing for ceramic tile installations. The target specification for concrete for this application was an industry requirement for a compressive strength of 2,500 psi with a panel weight of 3.2-3.6 lb/ft^2 using a cement-to-aggregate ratio of 1:2.5. Tests conducted at the facility of a panel manufacturer demonstrated that expanded slag in the 35-40 lb/ft^3 unit weight range met their requirements and may even perform better than the conventional materials due to its lower unit weight.

SLA was also successfully tested as a total and partial substitute for several conventional ULWA applications, namely insulating concrete, loose fill insulation, and nursery/horticultural applications. Perlite-based ULWAs have unit weights in the <4-12 lb/ft^3 range. However, since the lowest unit weight we achieved for expanded slag was about 18 lb/ft^3, we used SLA products ranging from 18 to 35 lb/ft^3 to evaluate its comparative performance in the ULWA applications.

It was concluded that SLA meets some of the requirements for expanded perlite. However, optimal results were obtained when SLA was used as a partial substitute for perlite products.

Insulating Concrete. Insulating concrete is used as an insulating layer in built-up roofs and is typically manufactured using expanded perlite or shale. The application requires a 200-psi concrete. The typical thermal conductivity of perlite (Group I) is 0.45-1.5 Btu-in/hr-ft^2-°F, and that of shale-based aggregates (Group II) is 1.5-3.0 Btu-in/hr-ft^2-°F. The thermal conductivity of concrete made using 26 lb/ft^3 SLA was 0.984 Btu-in/hr-ft^2-°F, which is superior to that of expanded shale but inferior to that of expanded perlite.

Loose Fill Insulation. Expanded perlite is used to fill cavities in blocks used for construction of building exterior walls to improve their insulation properties. The thermal resistance of 29 lb/ft^3 SLA was 1.46 hr-ft2-°F/Btu, which is lower than that of expanded perlite at 2.6-2.4 hr-ft2-°F/Btu. However, SLA has an advantage with respect to other industry requirements such as its free-flowing nature, low friability and hence low dustiness, and low moisture retention.

Horticultural Applications. SLA products with unit weights ranging between 18 and 35 lb/ft^3 were tested as partial substitutes for expanded perlite and vermiculite at a commercial nursery. The SLA proved successful as a partial substitute for perlite only but not for mixes calling for both perlite and vermiculite. The main problem with the SLA was its high drainage rate, which necessitated more frequent watering. However, its higher unit weight was seen as an advantage in providing greater stability to large potted plants and shrubs and its higher strength made it suitable for mechanized field/nursery applications.

Economics of SLA Production. The slag production economics were conducted using two parallel approaches:

- Comparison of the economics of SLA production vs. slag disposal
- Comparison of the economics of SLA production with the estimated market value of end products that can be made from it.

The market price of SLA was estimated taking into consideration the fact that it would likely command a lower price as a new, unproven material. The sale prices for slag lightweight aggregates were estimated at $30/ton for block aggregates, $35/ton for structural aggregates, and $40/ton for roof tile and ultra-lightweight aggregate applications. Using a product mix based on the percentage of coarse and fine slag, the weighted average price of SLA was estimated at $34.75/ton. This price was used to evaluate the economics of SLA production.

For purposes of this analysis, a value of $15/ton is used as the cost of slag disposal, which is in the middle of the range of $10-20/ton indicated for fly ash. Since these avoided costs would provide substantial savings to the gasifier operation, this amount could potentially be made available to the SLA production facility as a tipping fee per ton of slag accepted.

For the economic analysis, four scenarios were studied representing two sizes of IGCC facilities (200 MW and 400 MW) each using two methods of SLA production (rotary kiln and fluidized bed). For the rotary kiln processes, the SLA production costs were estimated at $30.07/ton and

$24.40/ton for the 200 MW and 400 MW sizes respectively (220 and 440 tons/day capacity). Conventional LWA production costs were estimated at $30.10/ton based on a survey of four operating plants.

The fluidized bed method of SLA production was found to be even more competitive because of lower capital and operating costs. Its production costs were $26.48 and $21.87 for the smaller and larger sizes respectively. Using the fluidized bed process for the manufacture of SLA, specially when disposal costs of slag are considered, can be economically attractive. The analyses performed as a part of the project indicate that payback periods of under three years can be achieved.

1.0 INTRODUCTION, OBJECTIVES, SCOPE, AND METHODOLOGY

1.1 Overview and Background Information

This document constitutes the final report (Topical Report No. 2) for Phase II of the project entitled "Utilization of Lightweight Materials Made from Coal Gasification Slags." This two-phase project (Cooperative Agreement No. DE-FC21-94MC30056) was awarded by the Department of Energy (DOE) to Praxis Engineers, Inc. Phase I consisted of production of expanded slag at the pilot scale, and Phase II consisted of testing and evaluation of the expanded slag as a replacement for conventional lightweight and ultra-lightweight aggregates. This document summarizes the findings of the Phase I work (reported in Topical Report No. 1) and provides detailed results of the Phase II work.

Primary funding for the project was provided by DOE's National Energy Technology Laboratory (NETL) at Morgantown, with significant cost sharing by the Electric Power Research Institute (EPRI) and Illinois Clean Coal Institute (ICCI). In addition, several industry participants provided significant in-kind cost sharing. These included:

- Fuller Company, a major manufacturer of lightweight aggregate kiln equipment
- Pennsylvania State University, where some of the development work and char removal testing was conducted
- Harvey Cement Products, Inc., where we made blocks from SLA using their block manufacturing plant
- Silbrico, a manufacturer of perlite products and expansion equipment
- Monier Lifetile, Inc., a producer of light weight concrete tiles
- Big River Industries, a manufacturer of lightweight aggregates
- Evergreen Nursery, where the horticultural application was tested
- Custom Building Products, a manufacturer of lightweight concrete panels.

Praxis Engineers, Inc., the prime contractor, also provided significant cost sharing.

The project team consisted of Praxis Engineers as the prime contractor, with significant participation from Fuller Company's R&D Division, as well as Harvey Cement Products, Silbrico, and Monier.

The integrated-gasification combined-cycle (IGCC) process is an emerging technology that utilizes coal for power generation and production of chemical feedstocks. However, the process generates large amounts of solid waste, consisting of vitrified ash (termed slag) and some unconverted carbon. In previous projects, Praxis investigated and developed the utilization of "as-generated" slag for a wide variety of applications in road construction, cement and concrete production, agricultural applications, and as a landfill material. From these studies, we found that it would be extremely difficult for "as-generated" slag to find large-scale acceptance in the marketplace, even at no cost. The reasons include the following:

- The unconverted carbon in the slag is detrimental to its utilization as sand or aggregate
- The physical characteristics of slag (particle size, shape, density, appearance, etc.) are different from those of the materials it could replace, such as sand or fine aggregates
- The materials it could replace are abundantly available at very low cost
- There is little existing data to validate the substitution of conventional materials, at least during the initial stages
- There is a widespread reluctance to use new materials due to potential liability issues.

Through a series of prior studies Praxis established that a variety of low- and high-volume applications for slag utilization need to be developed to help achieve the goal of near-total utilization of the slag generated at an IGCC facility. Figure 1 summarizes the concept of developing a variety of applications designed to achieve total utilization of slag. As may be seen, high-volume applications (such as aggregate in road base and sub-base) are typically also low-value applications. Conversely, several low-volume applications (lightweight and ultra-lightweight aggregates) are high-value applications. The development of a balanced mix of low-, medium-, and high-value applications would not only ensure total utilization of slag, but would actually generate a revenue stream for IGCC facilities while eliminating disposal costs. In addition, the wide variety of applications would help compensate for seasonal variations in the demand for some of the applications.

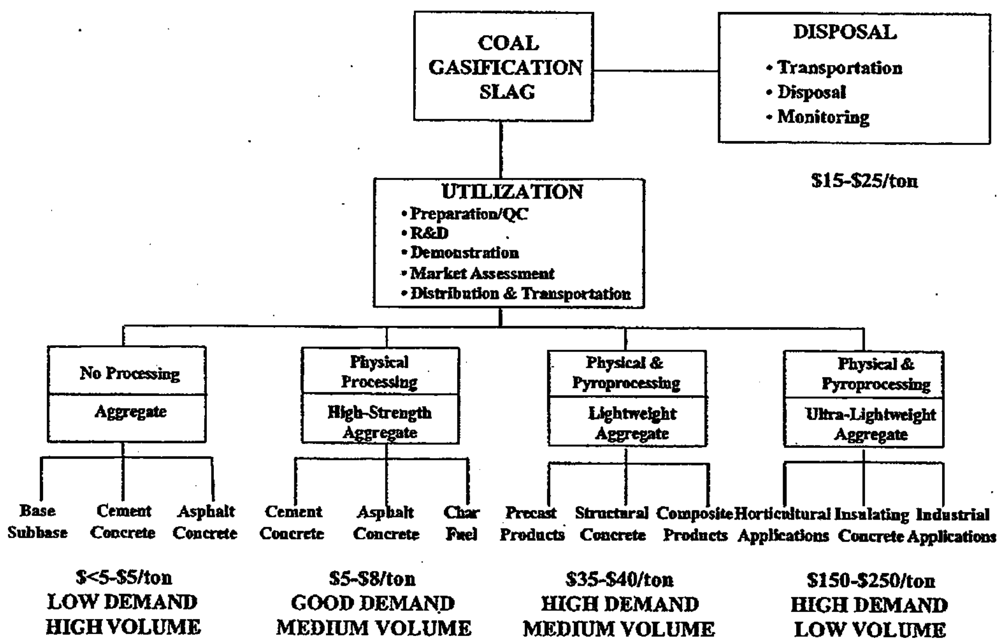

Figure 1. Slag Utilization Applications

It became apparent that the goal of total utilization of slag could be reached by developing a wide variety of value-added products from slag designed to meet specific industry requirements. This approach was made feasible through Praxis' discovery that slag undergoes expansion and forms a lightweight material when subjected to controlled heating in a kiln at temperatures between 1400 and 1700°F. This finding indicated the potential for using expanded slag as a substitute for conventional lightweight aggregates (LWA). The technology to produce lightweight and ultra-lightweight aggregates (ULWA) from slag was subsequently further developed by Praxis with funding from the Electric Power Research Institute (EPRI), Illinois Clean Coal Institute (ICCI), and internal resources. Patents on the "Utilization of Slag from Coal Gasification Systems" were granted jointly to Vas Choudhry of Praxis Engineers, Seymour B. Alpert of EPRI, and Donald Meisel of Texaco, (European Patent No. 90121365.2, awarded 13 December 1990 and U.S. Patent No. 5,091,349, awarded 25 February 1992).

The major objectives of the subject project were to demonstrate the technical and economic viability of commercial production of LWA and ULWA from slag and to test the suitability of these aggregates for various applications. The project goals were accomplished in two phases. Phase I comprised the production of LWA and ULWA from slag at the large pilot scale. This involved the collection of a 20-ton sample of slag (primary slag) from one source, with subsequent collection of additional samples of other slags for confirmatory testing of the processing steps. A 400-lb/hour pilot plant was set up at Penn State University's Materials Processing Laboratory to process the slag samples for char removal. Phase I testing also covered preparation and testing of project slag samples at the laboratory scale for their expansion characteristics to produce LWA. Upon completing the development work, pilot plants consisting of two sizes of rotary kilns and a fluidized bed expander were set up at the facilities of Fuller Company, a leading manufacturer of kiln equipment for the LWA industry. These pilot plants were used to pyroprocess various slags to produce large quantities of expanded slag aggregates of various size gradations and unit weights, ranging from 16 to 50 lb/ft^3. Environmental (emissions) data for slag lightweight aggregate (SLA) production were collected to identify the type of pollution control equipment that would be required. In addition, the char recovered from the slag preparation operation was evaluated for use as a kiln fuel and as a recycled feed material mixed with the coal gasifier feed.

In Phase II, the expanded slag aggregates were tested at the laboratory scale for their suitability in the manufacture of precast concrete products (e.g., masonry blocks and roof tiles), lightweight structural concrete, concrete panels, and insulating concrete. Subsequently some of these applications were evaluated at a larger scale with the involvement of commercial manufacturing plants, using ASTM and industry test methods. Technical data generated during production and testing of the products were used to assess the overall technical viability of expanded slag production and utilization. The testing was followed by an economic evaluation of the production and utilization of the SLA-based products. This was based on cost information provided by commercial manufacturers of the target products, as well as data gathered on the potential market price the SLA-based products might command once their quality had been validated through manufacturer testing.

1.2 Phase II Project Objectives

The objectives of Phase II were to test the use of expanded slag products in a wide variety of applications with the goal of partially or fully substituting slag lightweight aggregates (SLA) for conventional lightweight materials. The high-value end product applications that were tested are listed below:

Lightweight aggregate applications:
- Lightweight roof tiles
- Lightweight masonry blocks (also known as concrete masonry units or CMUs)
- Structural concrete
- Concrete panels

Ultra-lightweight aggregate applications:
- Insulating concrete
- Loose fill insulation
- Nursery application as a substitute for perlite and/or vermiculite

Relevant cost data for physical and pyroprocessing of slag to produce expanded slag aggregates were gathered for comparison with (i) management and disposal costs for slag or similar wastes, and (ii) production costs for conventional lightweight aggregates which the slag aggregates would replace. In addition, a market assessment was made to evaluate the economic viability of these utilization technologies.

1.3 Scope of Phase II Work

A summary of the tasks performed in Phase II is given below.

Task 2.1 Test Plan for Applications of Expanded Slags (Field Studies)

This task involved the development of selection criteria and a field test plan for applications of expanded slag. This plan served as a guide in the selection and implementation of field demonstrations for the most promising expanded slag utilization applications. Field applications were selected on the basis of laboratory results, the marketability of the products, and the suitability of the project slags for producing them. The following applications were considered for testing:

Lightweight aggregate applications:
- Lightweight roof tiles made from 40 lb/ft^3 SLA
- Lightweight masonry blocks made from 50 lb/ft^3 SLA
- Structural concrete made from 45-50 lb/ft^3 SLA
- Concrete panels made from 35-45 lb/ft^3 SLA

Ultra-lightweight aggregate applications:
- Insulating concrete made from 26 lb/ft^3 SLA
- Loose fill insulation made from 29 lb/ft^3 SLA
- Horticultural applications made from 15-18 lb/ft^3 SLA.

Task 2.2 Field Studies to Test Expanded Slag Utilization

Under this task, field testing of the applications identified in Task 2.1 began with test work to optimize the concrete mixes made from expanded slag.

Task 2.3 Data Analysis of Commercial Utilization of Expanded Slags

The objective of this task was to assimilate the data and test results collected during Phase II, convert these findings to common engineering terms, and correlate these results with comparable information for conventional lightweight aggregates as reported in the literature. The data analysis was done to provide specific answers to the following issues:
- Performance of expanded slag vs. that of conventional materials
- Technical viability of lightweight and ultra-lightweight slags as aggregates.

Task 2.4 Economic Analysis of Expanded Slag Utilization

The objective of this task was to expand upon the preliminary economic assessment of expanded slag utilization conducted during Phase I. The economics was studied based on the production costs for SLA in comparison with current market prices for conventional materials. During the Phase I preliminary evaluation, two production scenarios emerged:

- Production of SLA at the gasifier location (on-site production)
- Production of SLA at an existing lightweight aggregate facility (off-site production).

The impact of the avoided costs of slag disposal on the economics of SLA production were also evaluated. Slag utilization data and product samples were made available to commercial lightweight aggregate users for validation of estimated market prices. The impact of SLA market prices on the economics of SLA production were studied.

Task 2.5 Separation of Char from Slag for Tampa Electric Company IGCC Plant

The objective of this effort was to conduct laboratory-scale testing to process the slag from the Tampa Electric Company (TEC) IGCC facility for char removal, develop a conceptual design for a char removal facility, and present the results to the plant engineers.

Task 2.6 Testing of Slag as Raw Material Additive in Portland Cement Kiln Feed

The objective of this task was to conduct laboratory studies to test and evaluate the potential for using slag as a partial replacement in portland cement kiln feed. This included testing to evaluate the impact of various levels of slag addition on the clinker temperature.

Task 2.7 Utilization of Slag as Raw Material in Portland Cement (Pilot Testing)

The objective of this task was to conduct pilot-scale tests to confirm the laboratory-scale test results from Task 2.6. The kiln product was evaluated as cement after grinding.

Task 3.0 Final Report

The data generated and collected during the project were compiled in a final report for submittal at the end of the project. It comprises a comprehensive description of the results achieved, consistent with the Reporting Requirements. The report includes the original hypothesis of the project and presents the investigative approaches used, complete with problems encountered or departures from the planned methodology, and an assessment of their impact on the project results.

1.4 Project Methodology

The project methodology was as follows:

- Build on the developmental work done by Praxis under previous EPRI-funded projects to produce LWA from slag, ICCI-funded projects to produce ULWAs from slag, and internal studies to identify potential applications for expanded slag aggregates.
- Obtain the participation of potential users and producers of SLA products throughout the project in order to familiarize them with the capabilities of SLA.
- Seek the involvement of slag generators in order to keep them informed of the potential for utilizing slag as an alternative to disposal.
- Use conventional LWA production methods and equipment in order to minimize the process development and commercialization time frame and increase product acceptability to LWA and ULWA manufacturers and end-use industries.
- Conduct laboratory-scale testing using industry and ASTM methods for each application to develop techniques for substituting expanded slag for the conventional materials.
- Work with end-users to ensure that the development approach would be acceptable to them.
- Work at the manufacturer's facility for small-scale testing, where possible. Review the results jointly to finalize processing techniques before conducting final large batch runs.
- Have the final products tested by outside laboratories, where possible.
- Conduct economic evaluation with the involvement of industrial partners.

- Periodically present project results to DOE, EPRI, ICCI, and potential end users, as well as to the IGCC facilities which provided the slag samples. DOE project personnel were invited to such meetings.

1.5 Phase I Work Summary

The primary objectives of the Phase I experimental work were to demonstrate the feasibility of producing lightweight and ultra-lightweight aggregates from the primary slag (Slag I) and to generate a sufficient quantity of expanded slag lightweight aggregates (SLA) in the 15-50 lb/ft^3 range. The technology was also demonstrated for a second slag (Slag II) derived from an Illinois coal feedstock. The goal was to demonstrate the use of all size fractions of slag including fines, which were processed to make extruded pellets using a clay binder prior to expansion. Other goals included the collection of engineering data (energy consumption, material balances, and emissions) from pilot plant operations. The specific conclusions based on the work conducted in Phase I are given below.

1.5.1 Slag Processing for Char Removal

The primary slag sample was successfully processed for char removal. Prepared slag containing 100% ash was recovered at yields ranging between 66 and 68%. A char product containing 45-54% ash was also recovered and was evaluated as a potential gasifier feed and kiln fuel.

The char recovered from the first-stage separation was upgraded successfully to 30% ash (70% carbon). This material was evaluated as a gasifier feed.

1.5.2 SLA Production Using a Direct-fired Rotary Kiln

Slag expansion using a direct-fired rotary kiln was accomplished in two forms: (i) expansion of coarse (1/4" x 50M) slag in discrete particle form, and (ii) expansion of pellets made from extruded slag fines mixed with an expansive clay binder.

- Expansion of the 1/4" x 50-mesh size fraction of Slag I was demonstrated to be feasible in the rotary kiln as a single size interval. The slag could also be expanded in any other size interval within this range to meet the specific requirements of an end product.

- Temperature vs. density studies were conducted and product unit weights could be varied in the 30-50 lb/ft^3 range by means of temperature control. It was feasible to further reduce the product unit weight to 20 lb/ft^3 but lower unit weights posed potential fusion problems.

- The +10-mesh Slag II sample was expanded to produce a product with a unit weight of 20-30 lb/ft^3 at a temperature of 1450-1500°F.

- The expansion temperature was 400-500°F lower than that typically required for expansible clays and shale, which represents significant energy savings.

The objectives of expansion testing of the pelletized slag fines using an expansive clay binder were twofold: (i) to demonstrate the use of clay as a binder, and (ii) to demonstrate that the clay can be blended with slag fines for expansion. Both of these objectives were met. The following conclusions can be drawn from this work:

- Size enlargement of extruded pellets made from minus 50-mesh slag mixed with 20-50% by weight of a minus 20-mesh expansive clay binder was successful. The resulting aggregates had a size of 3/8" which could be controlled as desired.
- The use of higher proportions of slag resulted in lower pellet moisture, which would have a major effect on overall process fuel consumption requirements, with greater use of slag lowering fuel costs.
- The expansion temperature for clay and slag when completely mixed together is lower than that required for clay alone. The firing temperature for the 80/20 and 50/50 slag/clay blends tested is approximately 1800-1900°F, which is higher than the expansion temperature of slag by itself but lower than that of clay. There was no indication of fusion with any of the extruded mixtures fired up to 2000°F.
- Expanded products with unit weights ranging between 27 and 33 lb/ft^3 were produced. The expansion temperature for these samples was nearly 200°F lower than that typically required for conventional expansible clay pellets, which represents considerable energy savings for slag expansion.
- Successful expansion of pelletized slag/clay blends in a 50:50 ratio indicates that these two materials can be blended to produce lightweight aggregates.

1.5.3 SLA Production Using a Fluidized Bed Expander

The fluidized bed expansion method was selected to demonstrate the production of lower-unit-weight products because of its improved energy efficiency and better temperature control since feed particles do not come into contact with a flame. The objectives were to demonstrate the suitability of this expansion method and to test the acceptability of the recovered char as a fuel in the bed. These objectives were met, and the following specific conclusions were drawn:

- The various slag size fractions were expanded in discrete particle form in a pilot-scale fluidized bed expander to produce SLA products with unit weights ranging between 18 and 26 lb/ft^3.
- Similar results were achieved for extruded granulated slag pellets made from minus 50M slag fines to make minus 10M expanded aggregates.
- The use of char in the fluidized bed expander is theoretically feasible and was attempted. However, the results were inconclusive in the time budgeted for use of the pilot fluidized bed expander facility.

The SLA products were characterized in preparation for demonstration in various end-use applications. The results of RCRA testing indicated that the TCLP leachate heavy metals concentrations were considerably lower than RCRA requirements.

All of the Phase I objectives were met.

2.0 RESULTS AND DISCUSSION OF PHASE II WORK

2.1 Test Plan for Applications Testing of Expanded Slags (Field Studies) (Task 2.1)

At the beginning of Phase II, a Test Plan was developed for conducting a systematic laboratory evaluation of target applications for the expanded slags produced in Phase I. As a first step, selection criteria for these applications were developed by Praxis with input from potential users of the aggregates and testing laboratories to select appropriate field demonstration tests. The criteria included the following:

- There should be a close match between the physical properties of the SLA and those of the target substitute materials
- Market penetration in the targeted applications should be cost driven
- The application should not involve undue perceived liability.

Applications that met these criteria were selected for testing of the suitability of replacing conventional lightweight aggregates (LWAs) with expanded slag aggregates. They are listed below:

- Lightweight roof tiles
- Concrete blocks
- Structural concrete
- Waterproof panels (concrete panels).

The following applications were selected for testing of the suitability of replacing conventional ultra-lightweight aggregates (ULWAs) with expanded slag aggregates:

- Insulating concrete
- Loose fill insulation
- Horticultural applications.

Upon selecting the applications for testing, a field test plan entitled "Test Plan for Applications of Expanded Slags (Task 2.1)" was developed. It is attached with this report as Appendix A. As the testing advanced, the test plan was modified where needed based on test results, the performance of the expanded slags, and suggestions by potential commercial users. In many cases potential users of the expanded slag were involved in the laboratory evaluation, and a major portion of the testing was done in their respective laboratories. This helped in making rapid adjustments to the methodology of using expanded slag aggregates in place of conventional aggregates.

2.2 Field Studies to Test Expanded Slag Utilization (Task 2.2)

Upon completing the laboratory evaluation, a number of applications were selected for field testing. The evaluation activities covered in this task were:

- Development and optimization of structural and non-structural lightweight concrete applications using SLA
- Evaluation of SLA for lightweight roof tile manufacturing
- Manufacture and testing of masonry blocks using SLA
- Investigating the demonstration of other applications
- Disposal of residual samples.

The following selection criteria were established to select demonstration applications:

- Close match between properties of SLA and those of the conventional materials
- Availability of user's personnel for consultations to adapt SLA for their application
- Availability of plant and willingness to manufacture finished products using SLA
- Low potential risks associated with the application.

Field studies were conducted for the following applications:

- Lightweight block production
- Concrete panels
- Horticultural applications.

Data evaluation and the results of both laboratory and field studies are reported together in the following section.

2.3 Data Analysis of Commercial Utilization of Expanded Slags (Task 2.3)

The work under this task involved two major activities:

- Performance of expanded slag in the conventional applications
- Technical viability of the SLA products corresponding to conventional LWAs and ULWAs.

The first activity or subtask involved laboratory studies to evaluate whether expanded slag products meet the basic requirements for a particular application (e.g., bulk density, compressive strength, drying shrinkage, etc. as applicable). The second activity involved evaluation of more general issues such as whether the expanded slag meets the functional requirements of the application, whether it is amenable to the end user's manufacturing setup, and whether the end product can match the performance of the corresponding conventional products. The results of this evaluation are discussed for each application in this section.

2.3.1 Laboratory Evaluation of SLA for Roof Tile Application

The objective of this test program was to develop mix designs to produce sand and SLA-based cement concretes with compressive strengths in the 2500-4000 psi range and unit weights in the 115-105 lb/ft^3 range. The principal use of these high-strength cement-based materials would be as a replacement for 55 lb/ft^3 LWA to make lightweight roof tiles. Conventional concrete roof tiles are attractive for a number of reasons, including the fact that they are firesafe and have a conservative life expectancy of 50 years. They can also be fabricated in large quantities and in various colors. However, traditional concrete is too heavy to be used in re-roofing applications without the addition of costly heavy bracing in the roof structure. Using LWA, it is possible to manufacture roof tiles with reduced unit weight, thereby eliminating the need for additional support or bracing and reducing construction costs.

We tested the use of SLA I as a replacement for LWA by running tests with varying proportions of cement. We determined that, with the use of chemical additives, it is possible to produce cement concretes with a range of compressive strengths and unit weights. The SLA I samples that were tested are identified in Table 1, along with a control sample of commercially available structural aggregate. As indicated in the table, 3/4" coarse SLA aggregates produced by expanding 50/50 extruded slag fines/clay pellets were tested at three strength levels (complete matrix) whereas the other samples were tested at only one level of cement.

Table 1. Cement Levels to Test SLA I as Structural Aggregate

SLA Products Tested	Tentative Cement Level, Sacks/Yard^3
(i) 3/4" coarse SLA I (50/50 slag-clay pellets)	5½, 6½, and 7½
(ii) 1/4" x 50M SLA I crushed as 3/8" combined LWA	One level of cement
(iii) 3/4" expanded clay pellets (Control)	One level of cement

Exploratory tests were conducted to establish appropriate sand, water, and cement requirements in order to achieve the target mechanical properties. The strength and unit weight of the resulting concrete specimens were measured and, based on these results, final mix designs were developed for the various expanded slags.

The test method for compressive strength specified in ASTM C-109 was used to test the specimens. The three aggregates consisted of 100% expanded slag, 50/50 expanded slag/clay, and a 100% clay control sample provided by a commercial roof tile manufacturer. The 100% slag aggregates and the 50/50 slag/clay aggregates were sized to match the size distribution of the clay aggregates used by the roof tile manufacturer. Typically, a roof tile mix uses a cement-to-aggregate ratio of 1:2.5, along with various additives such as accelerators and superplasticizers. In order to mimic products available in the market for purposes of comparison, two different kinds of accelerators and a common commercial superplasticizer (Mighty 150) were evaluated. The accelerators tested were calcium chloride dihydrate ($CaCl_2 \cdot 2H_2O$) and sodium silicate. These were used to enable the products to set quickly and therefore increasing the manufacturing rate. Superplasticizers are used to reduce water requirements, thereby increasing strength.

During the testing, all of the aggregates were used in their saturated surface dry (SSD) condition as defined by ASTM. The moisture content of the three aggregates in their SSD condition was measured and recorded.

Because the specific mix formulations used by roof tile manufacturers are considered proprietary information and were therefore not available to us, we conducted many experiments with varying amounts of accelerator, superplasticizer, and water-to-cement ratios with the goal of obtaining the highest 7-day compressive strength without using excessive additives. Three 2" x 2" x 2" mortar cubes were cast and cured in a wet box (relative humidity of ~70%) for 2 hours and then steam-cured at ~60°C for 4 hours. The cubes were demolded and returned to the wet box for further curing to 7 days. The cubes were then weighed and broken in compression. A summary of the formulations and 7-day compressive strengths is presented in Table 2.

Table 2. Formulations and 7-Day Compressive Strength of Roof Tile Samples

Aggregate Type	$CaCl_2 \cdot H_2O$ Wt% of cement	Super-plasticizer Wt% of cement	Mortar Unit Wt lb/ft^3	Water/ Cement Ratio	SSD %	7-day Compressive Strength, psi
SLA	2	5.5	90.5	0.26	18	668
SLA	2	5	92.3	0.29	18	934
SLA	2	2	92.6	0.32	18.5	2303
SLA	2	2	93.3	0.35	18.5	2806
SLA	2	2	96.8	0.38	17.4	2028
SLA	2	2	97.1	0.41	17.4	1743
SLA		1.5	98.3	0.38	17.4	2650
SLA	2	1.5	101.7	0.38	18	2432
Control**	2	2	109.3	0.38	17	2011
Control**	2	2	108.7	0.41	17	2802
Control**	2	2	105.3	0.45	17	3390
Control**	2	2	105.2	0.50	17	3106
50/50 slag/clay	2	1.5	105.2	0.35	26	2303
50/50 slag/clay	2	1.5	101.9	0.38	26	1917
50/50 slag/clay	2	1.5	101.8	0.41	26	1736

* 1% sodium silicate was added for this test.

** Control aggregate was produced at a commercial kiln and provided by a roof tile manufacturer.

The highest 7-day compressive strength for the expanded slag specimens was 2806 psi, which is 83% of the highest strength obtained for the expanded clay samples. Visual inspection of the crushed SLA-based cubes revealed that the cement/aggregate interface was sound and that failure was chiefly due to aggregate breakage. This was confirmed by the specimens made from 50/50 slag/clay. The unit weight of the 100% expanded slag specimens ranged between 91 and 98 lb/ft^3, that of the 50/50 specimens between 102 and 105 lb/ft^3, and that of the 100% clay control specimens between 91 and 101 lb/ft^3.

These experiments showed that the mechanical behavior of the samples is greatly affected by the water/cement ratio but not by the type of accelerators used. Typically, in cement systems, lowering the water/cement ratio improves strength if care is taken to keep the mix workable. However, in the case of the expanded slags, the water/cement ratio had to be kept relatively high (>0.35) in order to have the cement paste coat all the particles and keep the structure together.

Additional tests were conducted to measure the 28-day compressive strength of SLA in the roof tile application. In these tests, a total of six different aggregates were used: an aggregate supplied by a lightweight roof tile manufacturer, expanded slag, 50/50 slag/clay, 80/20 slag/clay, expanded clay from the pilot test program, and an expanded clay aggregate sample provided by a leading LWA manufacturer. The commercial samples and the expanded clay produced during the pilot run were used as controls for purposes of comparison. The aggregates were first immersed in deionized water and allowed to soak for 4-6 hours. After soaking, the standing water was decanted and the aggregates were allowed to dry in ambient air until they were in a saturated surface dry condition, as defined by ASTM. The moisture content of the aggregates was measured by weighing a sample of the aggregate before and after drying in a 105°C oven overnight.

The basic mix design included the use of 1.5 ml of Mighty 150 superplasticizer per 100 gm of cement, 2wt% $CaCl_2 \cdot 2H_2O$ (relative to the amount of cement used), and just enough water to create a mix with a slump of 0-1. The aggregate/cement ratio was kept constant at 2.5:1 by weight. A common type I cement was used. The amounts of superplasticizer and accelerator were fixed while the water/cement ratio (w/c) was varied, depending on the aggregate used, until the desired slump was achieved. All mixing was done according to ASTM C 305 for mortars. Based on the 7-day compressive strength results (shown in Table 2), two final mix designs for each aggregate were selected. Six 2" x 2" x 2" specimen cubes of each mix design were cast. During molding, care was taken to ensure that the mixtures were well compacted. After mixing, the molds were placed in a covered wet bucket at room temperature for four hours, after which the specimens had sufficient strength to be demolded. They were then placed in a stainless steel tray with holes in the bottom, which was in turn placed in an unsealed plastic bag. The whole assembly was placed in a steam bath with a steam temperature of 60°C. The plastic bag prevented any hot water from dripping onto the cubes and eroding the samples. Since the bag was not sealed, there was no possibility of hydrothermal reactions. The cubes were steamed for four hours, then removed from the steam bath and further cured at room temperature in a covered wet box. Three cubes of each mix design were tested at 7 days and 28 days for compressive strength to failure according to ASTM C 109. Prior to testing, each cube was weighed and the average weight was used to calculate the unit weight. The mix design, average unit weights, and average compressive strengths are given in Table 3.

Table 3. 28-Day Compressive Strength Results for Roof Tile Application

Aggregate	Water/ Cement Ratio	SSD, %	28-Day Compressive Strength, psi	Unit Weight lb/ft^3
Commercial roof tile sample (control)	0.45	16.8	4789	102.2
Expanded slag	0.35	24.6	2823	94.5
50/50 slag/clay	0.35	19.6	2808	97.4
80/20 slag/clay	0.38	19.6	2940	99.7
Expanded clay (control)	0.65	19.0	3066	87.1
Big River clay (control)	0.40	15.1	7292	115.6

Superplasticizer (Mighty 150):	1.5 ml/100 g cement
Accelerator ($CaCl_2 \cdot 2H_2O$):	2% by weight
Aggregate-to-cement ratio (by weight):	2.5
Water-to-cement ratio:	to obtain 0-1 slump

As with the earlier experiments, the mechanical behavior of these samples was greatly affected by the water-to-cement ratio. The compressive strength of the 50/50 slag/clay sample was about 2800 psi, which is close to the value for the expanded clay sample at 3066 psi but lower than that of the 4789-psi control sample supplied by a lightweight roof tile company. The strength of the SLA-based concrete is considerably lower than that of similar products made from conventional lightweight aggregates. However, its unit weight at 97.4 lb/ft^3 is also lower than that of the manufactured aggregate-based concrete at 102.2 lb/ft^3. It is fair to assume that by producing a SLA-based concrete with a somewhat higher unit weight, the compressive strength would likewise increase.

Laboratory Evaluation of Slag III SLA for Roof Tile Application. The objective of this test program was to produce lightweight concrete suitable for the roof tile application from SLA III using a 50/50 ratio of Slag III and clay. As with the previous tests using Slag I, the compressive strength target requirement was in the 2500-4000 psi range, with corresponding unit weights in the 115-105 lb/ft^3 range. Although the compressive strength of the specimens in the previous tests using Slag I were 2800 psi and higher, we believed better particle size distribution of the aggregate in addition to refinement of the mix ratios would easily increase their compressive strengths.

The expanded slag aggregates used in the test program were made from a 50/50 blend of Slag III/clay which was crushed to match the size distribution of the LWA aggregates used by the roof tile manufacturer. The tests were performed using SLA III/clay in a saturated surface dry (SSD) condition as defined by ASTM. The moisture content of the aggregates was measured and recorded. Whereas both the accelerator and the superplasticizer were used in the earlier tests, in the current batch of tests (RT-1 and RT-2) only the superplasticizer was used.

Three 3" x 6" mortar cylinders were cast using the concrete mix formulation, cured in a wet box (relative humidity of ~70%) for 2 hours, and then steam-cured at ~60°C for 4 hours. The cylinders were demolded and returned to the wet box for further curing to 7 days. The cylinders were then weighed and broken in compression. A summary of the formulations and 7-day compressive strengths is presented in Table 4. The highest 7-day compressive strength for the SLA III specimens was 5600 psi, which is considerably higher than the previous best results of 2800 psi for SLA I and exceeds the ASTM requirement of 4000 psi. One reason for these good results is that baghouse dust fines were added to the SLA III aggregate and used in the mix. The resultant mixture thus had a higher unit weight but, more importantly, had a much better particle size distribution. The unit weights of the specimens made from SLA III ranged between 113.6 and 114.6 lb/ft^3.

Table 4. Evaluation of SLA III as Aggregate in Roof Tile Application

LWA	SSD M%	$CaCl_2 \cdot H_2O$ Wt% of cement	Plasticizer Wt% of Cement	Water/ Cement Ratio	LWA/ Cement Ratio	Mortar Unit Wt lb/ft^3	Compressive Strength 7-day, psi
50/50 SLA III Test No RT1	18.1*	-	2	0.57*	2.5	113.6	5598
50/50 SLA III Test No RT2	18.1*	-	2	0.47*	2.5	114.6	5603
SLA I**	18.5	2	2	0.35	2.5	93.3	2806
Commercial LWA**	17.0	2	2	0.45	2.5	105.3	3390
Slag/Clay**	26.0	2	1.5	0.35	2.5	105.2	2303

*SLA was used in "as is" dry form using a higher cement-to-water ratio. However, the SSD moisture and water-to-cement ratios were calculated using another sample and reported for comparison.
** Tests conducted with SLA I and commercial aggregate used by the roof tile manufacturer as reported in Table 2.

Superplasticizer (Mighty 150):	1.5 ml/100 g cement
Accelerator ($CaCl_2 \cdot 2H_2O$):	2% by weight
Water-to-cement ratio:	to obtain 0-1 slump

Some of the cylinders with RT1 and RT2 were allowed to cure further to obtain 28-day compressive strengths. The results are given in Table 5. These results were compared with those for tests conducted using the best conditions selected from the work done with SLA I.

Table 5. 28-Day Strength Results of SLA in Roof Tile Application

Aggregate	W/C	SSD	Unit Weight lb/ft^3	28-Day Compressive Strength, psi
SLA III-RT1	0.75	18.1*	113.6	5603
SLA III-RT2	0.65	18.1*	114.6	6421
Roof tile plant aggregate	0.45	16.8	102.2	4789
SLA I	0.35	24.6	94.5	2823
Slag/clay 50/50	0.35	19.6	97.4	2808
Commercial aggregate	0.40	15.1	115.6	7292

*SLA was used in "as is" dry form using a higher cement-to-water ratio. However, the SSD moisture and water-to-cement ratios were calculated using another sample and reported for comparison.

As may be seen in Table 5, the Slag III/clay mix resulted in a compressive strength of 5600-6400 psi, with corresponding unit weights of 114-115 lb/ft^3. This is the first time that such a high strength has been obtained using an expanded slag aggregate. Unlike the tests using SLA I, these high-strength samples were made from higher-unit-weight SLA and contained no accelerator, which enables the manufacturers to demold their samples earlier but also may reduce ultimate strength in the longer term.

Based on these data, we proceeded to develop a commercial SLA mix design and verify the high compressive strengths by repeating some tests. Evaluation of the data and visual examination of the previous samples indicated that they were deficient in fines. Therefore, the original tests (RT-1 and RT-2) and the repeat tests RT-3 and RT-4 were performed using Slag III/clay along with large quantities of fines generated during the production of the same product. The roof tile aggregate mixes for tests RT-1 and RT-3 used 75% fines and those for tests RT-2 and RT-4 used 50% fines. The expanded fines were added to provide continuity in the gradation of the aggregate and cement. The particle size distribution of the expanded Slag III/clay blend is given in Table 6.

Table 6. Size Gradation of Aggregate Mix Used in Roof Tile Tests

Size Fraction	Coarse Aggregate Slag III/Clay	Fine Aggregate Cyclone Fines	RT-3 Mix	RT-4 Mix
	10 x 50M		25/75*	50/50*
	Wt%	Wt%		
4 x 8M	0.1	53.0	39.8	46.4
8 x 16M	1.3	40.6	30.8	35.7
16 x 30M	18.6		9.5	7.9
30 x 50M	13.1	0.0	3.3	1.6
50 x 100M	9.4	0.0	2.4	1.2
100x 200M	10.9		2.7	1.4
200M x 0	46.6	0.0	11.7	5.8
	100.0	100.0	100.0	100.0

*Proportion of expanded Slag III/clay vs. cyclone fines.

Aggregate mix evaluated	10 x 50M Slag III/clay 50/50 mixed with fines
Superplasticizer (Mighty 150):	2.0 ml/100 g cement for all tests
Accelerator ($CaCl_2 \cdot 2H_2O$):	2% by weight where indicated
Aggregate-to-cement ratio (by weight):	2.5
Water-to-cement ratio:	to obtain 0-1 slump

The roof tile concrete mixes were prepared using the same procedure as was used for the previous batch of tests (RT-1 and RT-2). The results of these tests are shown in Table 7 along with previous results for comparison.

Table 7. Evaluation of SLA III as Aggregate in Roof Tile Application

Test No.	Aggregate/Fines		Water/ Cement Ratio	Mortar Unit Wt (lb/ft^3)	Compressive Strength (psi)	
	Coarse	Fines			7-day	28-day
Slag III/Clay 50/50 aggregate blended with fines						
RT-3	25	75	0.57	104.4	5043	5902
RT-4	50	50	0.47	107.2	6801	6991
RT-1	25	75	0.57	113.6	5598	5603
RT-2	50	50	0.47	114.6	5603	6421
Other Aggregates						
SLA I	100	-	0.35	93.3	2806	2823
Roof tile plant LWA (control)	100	-	0.45	105.3	3390	4789
Slag I/Clay*	100	-	0.35	105.2	2303	2808

* Tests conducted with SLA I and commercial aggregate used by the roof tile manufacturer were done previously using a plasticizer (2% by weight of cement) and $CaCl_2 \cdot H_2O$.

Note: Tests RT-1, RT-2, RT-3 and RT-4 were done using a 50/50 mixture of expanded Slag III and clay with only plasticizer (2% by weight of cement).

As may be seen in Table 7, the Slag III/clay mixes (RT-3 and RT-4) resulted in compressive strengths of 5000-6800 psi in 7 days with corresponding unit weights of 114-115 lb/ft^3. The 28-days strengths were even higher, ranging from 5600 psi to almost 7000 psi. These tests demonstrated that expanded slag/clay blends can be used to produce concrete suitable for the roof tile application.

2.3.2. Lightweight Masonry Blocks (CMUs)

The objective of this subtask was to use commercial-scale concrete block manufacturing equipment and techniques to produce masonry blocks (also known as concrete masonry units or CMUs) from expanded slag lightweight aggregates (SLA). This work was done at the facilities of a major block manufacturer and distributor in the greater Chicago area. The LWA manufacturer was selected as their facility is located near the Wabash River IGCC plant that would be a potential permanent source for slag and hence SLA. A number of block mix designs were developed by Praxis using particle size distribution and unit weight information provided by the manufacturer. These mix designs were first tested in the laboratory in order to optimize them. We then prepared trial batches of concrete, followed by a full-scale run using their commercial batching plant and continuous block machine.

The objective in developing the mix designs was to substitute sufficient portions of SLA for conventional LWA in the mix while maintaining the proportions of other aggregates as per current commercial practice. Since each manufacturer has a choice of a variety of aggregates, mix designs were developed to test a number of blends. The particle size distribution of the aggregates normally used by the plant is shown in Table 8. Also shown in the table are with the size distribution of fine SLA (SLA/F) produced from 10 x 50M SLA I and coarse SLA (SLA/C) produced from coarse (1/4" x 10M) slag feed. The size gradation is critical as it determines the workability of the block mix and also directly affects the mechanical property of the blocks. Therefore, mixes should conform to the gradation range provided by the manufacturer as a guideline. Using these guidelines, five mix designs (SLA Mix Nos. 1-5) were selected for testing and submitted for review by the manufacturer.

Table 8. Size Distribution of Aggregates Used for Concrete Block Application

Size Fraction	LSS*, Wt%	Sand Slag** Wt%	SLA/F Wt%	SLA/C Wt%	LWA (P)*** Wt%
+3/8"	0.0	0.0	0.0	3.5	0.0
3/8" x 4M	0.2	9.3	0.5	8.7	1.3
4 x 8M	18.2	26.2	9.2	61.5	26.5
8 x 16M	30.7	20.1	54.8	24.1	25.6
16 x 30M	19.4	14.8	23.0	1.1	17.0
30 x 50M	13.0	11.8	10.8	1.1	11.9
50 x 100M	9.2	8.7	1.7	0.0	7.3
100M x 0	9.3	9.1	0.0	0.0	10.4
Total	100	100	100	100	100
Unit wt, lb/ft^3	83.8	88.2	43.9	44.7	52.9

* LSS: Stone dust used by the plant (by-product)
** Blast-furnace slag fines used in place of concrete sand
*** LWA (P): Conventional LWA used by the plant.

ASTM C 331 specifies unit weight values for aggregates and unit weight and strength requirements for cement concrete used in manufacturing lightweight concrete masonry units. These requirements are summarized in Table 9.

As would be expected, the strength requirements for load-bearing blocks are higher than for nonload-bearing blocks. However, from the viewpoint of block production there is no real advantage to producing nonload-bearing blocks whereby small quantities of cement may be saved but a different product line is involved. The standard does not specify the cement concrete mix design for blocks, thus allowing a degree of flexibility in the choice of aggregates and cement-to-aggregate ratios.

Table 9. LWA and Cement Concrete Requirements for CMU Applications

Lightweight Aggregate Unit Weight Requirements for CMU (ASTM C 331)				
		Fine lb/ft^3	**Coarse lb/ft^3**	**Combined lb/ft^3**
Unit weight, max. values		70	55	65
Industry preference		NA	NA	50
Lightweight Concrete Unit Weight and Strength Requirements for CMU				
			28-Day Compressive Strength	
	ASTM	**Unit Weight lb/ft^3**	**Gross psi**	**Net* psi**
Load-bearing				
- below grade	C 90	<105	1000	2000
- above grade	C 90	<85	700	1400
Nonload-bearing	C 129	105	NA	600

*Net compressive strength values calculated by assuming net cross-sectional area is 50% of gross area.

Laboratory Testing of Concrete Block Formulations. After two types of expanded slag materials were delivered at the concrete block facility, mix designs were prepared in the laboratory to test their compressive strength, rate of strength increase over 3-, 7-, and 28-day periods, and the unit weight of the concrete. Test mixes were formulated with the objective of manufacturing two types of blocks:

- Normal-weight blocks with a dry weight of approximately 33.5 lb
- Lightweight blocks with a dry weight of approximately 27 lb.

For both block mixes, the conventional lightweight aggregate LWA (P) used by the plant was replaced by slag lightweight aggregates of two types:

- Fine slag lightweight aggregate produced from 10 x 50M slag feed (SLA/F)
- Coarse slag lightweight aggregate produced from 1/4" x 10M slag feed (SLA/C).

The results of exploratory tests using the mix designs used for block production are shown in Table 10. As may be seen, the cement-to-aggregate ratio used was identical to that currently used at the plant. For lightweight blocks, the cement-to-aggregate ratio was 1:6.6, and for regular blocks it was 1:8.7. Water was added on an as-required basis depending on the overall workability of the aggregates and the cement paste in the mix.

Table 10. Results of Batch Mix Tests Conducted for Masonry Blocks Using SLA

	Materials Used by Volume, ml							Compressive Strength, psi		
Test Batch	**LSS**	**SS**	**SLA/F**	**SLA/C**	**Total Aggr.**	**Cement**	**Concrete Unit Wt lb/ft³**	**3-day**	**7-day**	**28-day**
Unit wt, lb/ft³	83.8	88.2	43.9	44.7		94.0	NA	NA	NA	NA
Regular-weight block mixes (cement-to-aggregate ratio of 1:8.7 by volume)										
21997-1	1650	630	720	-	3000	346	160.4	1090	1246	1636
21997-2	1650	630	-	720	3000	346	166.9	1285	1324	1519
Lightweight block mixes (cement-to-aggregate ratio of 1:6.6 by volume)										
21997-3	1290	-	1710	-	3000	453	126.3	1012	1168	1402
21997-4	1290	-	-	1710	3000	453	123.9	934	1012	1168
21997-5	645	-	855	0	1500	264	122.3	1051	-	1519

Test specimens (2" x 4" cylinders) were made from the concrete and stored in a curing chamber used to cure commercial blocks. A total of nine specimens were made for each batch, which allowed for three cylinders per compression test. These tests were conducted after 3, 7, and 28 days of curing. For the last batch, only six specimens were made, which were tested after 3 and 28 days of curing.

The compression test results indicate that at the 1:8.7 and 1:6.6 cement-to-aggregate ratios, the 28-day strength was below the ASTM requirement of 2000 psi for load-bearing blocks. Adjusting the mix by adding a higher proportion of cement to the mix or increasing the slag sand or limestone sand content may increase these strength values.

The specimens made using fine expanded slag (SLA/F) proved to have higher compressive strength than those made from the coarser expanded slag (SLA/C). For example, a regular block mix using SLA/F (Test 21997-1) had a 28-day compressive strength of 1639 psi, while one made using SLA/C had a strength of 1519 psi (Test 21997-2). A similar trend was apparent in the case of lightweight blocks in which higher quantities of SLA were used.

The test results were discussed with the manufacturer and it was concluded that the lower strength values were obtained because the aggregate blend was not cohesive. Therefore, additional batches of tests were run using SLA I. During this phase of the testing, the cement-to-aggregate ratio used was identical to that currently used at the plant. As may be seen in Table 11, for the regular blocks (Mix 30S), the cement-to-aggregate ratio was 1:8.22, and for the lightweight blocks (Mix 19S) it was 1:5.97. However, a third test (Mix 19x1S) was prepared using a slightly higher cement-to-aggregate ratio of 1:5.64, with a lower quantity of the lighter-weight SLA. Water was added on an as-required basis depending on the overall workability of the aggregates and the cement paste in the mix. Test specimens (2" diameter, 3.5" tall cylinders) were made from the concrete and stored in a commercial block-curing chamber. A total of three specimens were made for each batch. The compressive strength was measured after 28 days of curing, and the average values are reported in Table 11.

Table 11. Results of Batch Mix Tests for Masonry Blocks Using SLA (2)

	Materials Used by Volume, ml						Concrete	
Test Batch	**LS**	**SS**	**SLA/F**	**SLA/C**	**Total Aggr.**	**Cement**	**Unit Weight lb/ft^3**	**28-day Strength psi**
Unit wt, lb/ft^3	83.8	88.2	44.7	43.9		94.0	-	-
Regular-Weight Block Mix No. 30S (cement-to-aggregate ratio = 1:8.22 by volume)								
Aggregate Mix	55.0	21.0	24 (SLA/F or /C)		100			
82797-1	1650	630	720	-	3000	346	110.1	1558
82797-2	1650	630	-	720	3000	346	117.9	1791
Lightweight Block Mix 19S (cement-to-aggregate ratio = 1:5.97 by volume)								
Aggregate Mix	43.0		57.0		100			
82797-3	1290	-	1710	-	3000	453	86.5	1402
82797-4	1290	-	-	1710	3000	453	78.6	1090
Lightweight Block Mix No. 19x1S (cement-to-aggregate ratio = 1:5.64 by volume)								
Aggregate Mix	60.0	-	40.0		100			
82797-6	1800	-	1200	0	3000	494	102.2	2180

The regular-weight block mix specimens using SLA/F (Test 82797-1) had a 28-day compressive strength of 1558 psi, while one made using SLA/C had a strength of 1791 psi (Test 82797-2). The unit weight of the concrete (110-118 lb/ft^3) was considerably lower than the typical value of 150 lb/ft^3 for regular blocks.

Tests with lightweight block Mix 19S resulted in compressive strengths of 1090-1402 psi, which is consistent with the low unit weight of the concrete (78.6-86.5 lb/ft^3).

The next batch of tests (Mix 19x1S) was conducted using a reduced proportion of SLA/F (40%) in order to increase the concrete unit weight and compressive strength. The 28-day strength for this mix (Test 82797-6) was 2180 psi, which is higher than the ASTM requirement of 1400 psi for above-grade blocks and 2000-psi for below-grade load-bearing blocks. The estimated weight of the block if made from Mix 19S was 20.4 lb, and that of the block made from Mix 19x1S was 22.3 lb. Both of these are below the preferred weight of 23 lb for lightweight blocks, which is excellent from the viewpoint of the industry. It was possible to further increase the strength of the SLA concrete by adding some fine sand to compensate for the lack of fines in the slag. However, this would increase the unit weight of the block.

Laboratory Evaluation of Expanded Slag III for Testing of Masonry Blocks: In order to verify the use of SLA in making lightweight blocks, Slag III was tested similarly. Test mixes were formulated based on the experience with the work done using Slag I.

The conventional lightweight aggregate was replaced by fine SLA III made from a 10 x 50M Slag III feed (SLA III/F). The cement-to-aggregate ratio used was identical to that currently used at the block manufacturing plant. Test specimens (2" diameter, 3.5" tall cylinders) were made from the concrete and stored in a steam chamber. A total of three specimens were made for each batch. The compressive strength was measured after 7 days (1 specimen) and 28 days (2 specimens) of curing, and the average 28-day values are reported in Table 12.

As may be seen in Table 12, the unit weights of specimens made with SLA III varied between 87 and 118 lb/ft^3 with a maximum compressive strength of 1550 psi.

Table 12. Results of Batch Mix Tests for Masonry Blocks Using SLA III

Test No.	Materials Used by Volume, ml					Concrete		
	Sand		SLA-III/F	Total Aggr.	Cement	Unit Weight lb/ft^3	Comp. Strength, psi	
	Washed	Unwashed					7-day	28-day
Unit wt, lb/ft^3	106.6	103.9	41.0		94.0	-	-	-
Cement-to-aggregate ratio = 1:7.73 by volume								
LB1	1978	--	1616	3594	465	114.6	1225	1380
Cement-to-aggregate ratio = 1:8.66 by volume								
LB2	--	2344	1683	4027	465	117.9	1012	1029
Cement-to-aggregate ratio = 1:6.74 by volume								
LB3	--	2344	1683	4027	598	108.7	930	1102
Cement-to-aggregate ratio = 1:7.46 by volume								
LB4	--	2783	1683	4466	598	115.9	1309	1575
Cement-to-aggregate ratio = 1:7.46 by volume								
LB5	--	2930	1530	4460	598	114.2	924	1273
Cement-to-aggregate ratio = 1:9.59 by volume								
LB6	--	2930	1530	4460	465	108.2	423	689
Mix 30S (cement-to-aggregate ratio = 1:8.22 by volume) Regular block								
Aggr. Mix	55% (LSS)	21% (SS)	24%	100%			-	-
82797-1 SLA I/F	1650 LSS	630 SS	720	3000	346	110.1	-	1558
Lightweight Block Mix No. 19S (cement-to-aggregate ratio = 1:5.97 by volume)								
82797-3 SLA I/F	1290	-	1710	3000	453	86.8	-	1402

These tests were also compared with results for SLA I (mix designs 30S and 19S). The regular-weight block mix using SLA I/F (Test 82797-1) had a 28-day compressive strength of 1558 psi, while one made using SLA I/C had a strength of 1402 psi (Test 82797-3). The unit weight of the concrete was considerably lower than the typical value required for regular blocks. Tests with lightweight block Mix 19S resulted in compressive strengths of 1090-1402 psi, which is consistent with the low unit weight of the concrete (78.6-86.5 lb/ft^3).

Additional tests were conducted in order to improve the compressive strength of the concrete. One test (LB-7) was performed to increase the strength to a target of 2000 psi by using a slightly higher quantity of cement (658 ml vs. 630 ml). The results are given in Table 13.

Table 13. Additional Results of Batch Mix Tests for Masonry Blocks Using SLA

Test ID	Type I Cement ml	SLA III ml	Unwashed Sand, ml	Mighty 150, ml	Unit Wt. lb/ft^3	7-Day Strength psi	28-Day Strength psi
LB-7	658	1616.4	2343.6	13.5	108	1531	1998

As may be seen, the unit weight of the concrete specimens was 108 lb/ft^3 and the compressive strength was nearly 2000 psi. Analysis of the mix indicated that in spite of the addition of sand, it was deficient in minus 100-mesh fines. Based on this assessment, we decided to make a mix with additional fines in the form of a mineral filler. This filler, a fine aggregate dust, is another process by-product used by the plant.

Commercial Production of Masonry Blocks. Based on the experience acquired with SLA I and SLA II, the mix design for the production batch of blocks, given in Table 14, was finalized. The mix batch was calculated to make 250 8-inch blocks. The concrete mix batch size was 4,222 lb using 60 ft^3 of aggregate (40% SLA). Sufficient water was added to achieve the desired consistency. The ingredients were weighed and dumped in the plant feed hopper and the automated process for mixing and transportation was initiated using the batching plant and standard three-mold continuous block machine operated at a nominal rate of 250 blocks/hour.

The target specification for the 8-inch lightweight blocks was to achieve a concrete unit weight of <105 lb/ft^3, which would result in a block dry weight of approximately 27 lb. The compressive strength target of the concrete would be 2,000 psi.

Table 14. Mix Proportions for Production Batch of Lightweight Blocks

	LSS*	SLA III 10 x 50M	Mineral Filler	Masonry Sand	Total	Type I Cement	Additive
Wt. %	52	40	5	3	100		-
Wt. (lb)	2226	1616	234	2344	3622	600	
Unit Wt. (lb/ft^3)	71.36	42.6	78.0	77.1	--	94	128
Vol. (ft^3)	31.2	24.0	3.0	1.8	60	6.38	48

* LSS: Local, normal-weight aggregate used by the plant.

Compressive strength and unit weight test results conducted on randomly selected blocks are given in Table 15.

Table 15. Compressive Strength and Unit Weight Test Results for Lightweight Blocks

28-Day Compressive Strength, psi	
Block 1	2041
Block 2	2098
Block 3	2190
Average	2143
Unit Weight, lb/ft^3	
Block 4	105.7
Block 5	105.3
Block 6	106.7
Average	105.9

The overall test results for the utilization of SLA in making lightweight blocks are summarized in Table 16.

Table 16. Summary of Test Results for Use of SLA in Lightweight Block Application

	Required Values	Tested Values
Net area compressive strength, psi	1900.00	2143
Gross area compressive strength, psi		1093
Density, lb/ft^3	<105	105.9
Absorption, lb/ft^3	18.00	11.4
Minimum face shell thickness, in.	1.25	1.25
Minimum web thickness, in.	0.75	1.00
Equivalent web thickness, in.	2.25	2.33
Equivalent thickness, in.		3.88
Net cross-sectional area, in^2		60.8
Net volume, ft^3		0.26
Percent solids, %		51.0
Calculated Fire Resistance Rating (NCMA-TEK 7-3), hr		1.75

As may be seen, the compressive strength for lightweight blocks using SLA was over 2,000 psi using the quantity of cement that is typically used by the industry. Also, a concrete unit weight of 106 lb/ft^3 was obtained using 40% SLA, which is the LWA level currently used by the manufacturer, i.e., 100% replacement. The blocks met all other requirements. The test program was considered successful since all relevant requirements were met.

2.3.3 Laboratory Evaluation of SLA for Structural Concrete Application

The objective of this test program was to develop mix designs to produce sand and SLA-based cement concretes with compressive strengths of 2500-4000 psi and corresponding unit weights in the 115-105 lb/ft^3 range. These variations were accomplished mainly by changing the proportion of cement relative to the SLA. The SLA samples tested are identified in Table 17. In addition, a control sample of commercially available structural aggregates was also tested. As may be seen in Table 1, the 3/4" coarse SLA was tested using three different cement levels to produce products with varying strengths (complete matrix) whereas the other samples were tested at only one strength level.

Table 17. Cement Levels Used in Testing SLA as Structural Aggregate

Test No.	SLA Products Tested	Cement Level, Sacks/Yard^3
1	3/4" coarse SLA (50/50 slag-clay pellets)	5½, 6½, and 7½
2	1/4" x 50M SLA I crushed as 3/8" combined LWA	One level of cement
3	3/4" expanded clay pellets produced during the pilot program	One level of cement

ASTM C 330 unit weight requirements for structural concrete aggregates are summarized in Table 18. Also provided in this table for purposes of reference are the unit weight and compressive strength requirements for cement concrete mixtures produced from 100% LWA or various mixtures of LWA and sand.

Table 18. LWA and Concrete Unit Weight and Strength Requirements

Structural Lightweight Aggregate Unit Weight Requirements			
	Fine	**Coarse**	**Combined**
	lb/ft^3	**lb/ft^3**	**lb/ft^3**
Unit weight, maximum values	70	55	65
Lightweight Structural Concrete Unit Weight and Strength Requirements			
Concrete Unit Weight	**28-Day Compressive Strength**		
lb/ft^3	**lb/in^2**		
All Lightweight Aggregate			
110	4000		
105	3000		
100	2500		
Sand-Lightweight Aggregate			
115	4000		
110	3000		
105	2500		

Table 19 lists the SLA-based aggregates and control aggregates that were tested. The table also provides the size gradation specified in ASTM C 330 in conformity with which the aggregates were prepared.

Table 19. Samples of Materials Used for Structural Aggregate Testing

Sample ID	**Aggregates and Production Methods**	**Gradation to ASTM C 330**	**Unit Weight lb/ft^3**
951132	Pelletized slag/clay (50/50 SLA)	3/4" coarse	40.9
951133	Clay LWA produced in pilot plant from clay used as binder to produce 50/50 SLA pellets	3/4" coarse	48.9
950931	SLA produced from 1/4" x 50M Slag I	3/8" combined	51.2
960234	Commercial LWA product (expanded clay)	5/8" coarse	34.0
960235	Commercial LWA product (expanded clay)	3/4" coarse	38.0
960233	Commercial LWA product (expanded clay)	3/8" combined	53.8
	Concrete sand	Fine size (4M x 0)	102.0

Clay LWA and commercial LWA were used as control materials. The slag- and clay-based expanded aggregates produced in the pilot plant were crushed to meet ASTM C 330 size specifications prior to use. The samples of commercial LWAs were obtained from a commercial LWA plant and used without crushing in the control tests since they were prepared to the appropriate ASTM size gradation specification. The size distribution of these materials is given in Table 20. The data indicate that the size distributions of SLA and 50/50 SLA (both prepared as 3/4" coarse aggregates) are much coarser than commercial aggregates with the same designation although they fall within the allowable range.

Table 20. Size Distribution of LWA Materials and Sand Used in Structural Concrete

	Commercial LWA			**50/50 SLA/LWA**	**Clay LWA**	**SLA**	**Sand**
ASTM C 330 Size	5/8" coarse	3/4" coarse	3/8" combined	3/4" coarse	3/4" coarse	3/8" combined	
Unit weight lb/ft^3	34.0	38.0	53.8	40.9	48.9	51.3	
Size Distribution, Wt% passing							
1"	100.0	100.0	100.0	100.0	100.0		
3/4"	100.0	100.0	100.0	100.0	100.0		
1/2"	81.3	95.9	100.0	52.1	33.8		
3/8"	27.5	68.2	100.0	21.1	11.8	100.0	100.0
4 mesh	12.6	6.1	97.0	8.4	4.4	91.9	99.0
8 mesh	8.5	3.1	70.5			59.9	77.0
16 mesh	6.0	2.5	41.3			50.3	55.0
30 mesh	4.0						41.0
50 mesh	3.3	1.7	14.2			20.5	
100 mesh	2.4	--	8.9			15.0	7.0
200 mesh							1.9

Table 21 lists the SLA and control tests that were carried out using different cement levels.

Table 21. Expanded SLA Products Tested and Cement Levels Used

No.	**Lightweight Aggregate Products Tested**	**Concrete Cement sacks/yard^3**
Sand-Lightweight Aggregate Tests		
1.	50/50 SLA as 3/4" coarse aggregates	5½, 6½, and 7½
2.	SLA (from 1/4" x 50M Slag I) as 3/8" combined aggregates	Min. one level of cement
3.	Clay LWA produced in the pilot plant from the clay used as a binder for producing 50/50 SLA	Min. one level of cement
4.	Commercial LWA product (expanded clay)	Min. one level of cement
All Lightweight Aggregate Tests		
5.	SLA (from 1/4" x 50M slag) as 3/8" combined aggregates	One level of cement
6.	Clay LWA produced in the pilot plant from clay used as a binder for producing 50/50 SLA	One level of cement

Testing and Evaluation Procedure. Cement concrete mixes were prepared from the slag aggregates listed above. The aggregate-to-cement ratios used were identified in exploratory tests, with the objective of achieving 28-day strengths of 2500, 3000, and 4000 psi, respectively. Approximately 12-15 test specimens were prepared for testing using the following procedure:

- Adjust the moisture content of the aggregates to saturated surface dry (SSD) conditions by saturating them in water overnight. Document the moisture content.

- Estimate the sand content required for the concrete mix to achieve a suitable gradation without exceeding the unit weight specification.

- Document the dosages of the air-entraining agent used.

- Prepare test specimens using the SLA sample with a pre-selected aggregate-to-cement ratio and slump. Measure the water added to document the cement-to-water ratio.

- Document the total weight and volumes of the ingredients used and calculate the sand-to-LWA ratio and water-to-cement ratio by weight. Measure the unit weight of the fresh concrete. Report the workability of the mix.

- Test a minimum of three specimens for compression following 1-day (early strength), 3-day, 7-day, and 28-day curing time periods. Save 3 cylinders for further testing.

- Prepare control test specimens using the commercial LWA sample with an identical aggregate-to-cement ratio and slump. Measure the water added to document the cement-to-water ratio. Measure the unit weight of the concrete and its compressive strength for 3-day, 7-day and 28-day curing time periods for purposes of comparison.

- Test specimens were saved in order to conduct the following tests at a later date if desired:
  - Freeze/Thaw, ASTM C 666
  - Drying Shrinkage, ASTM C 157
  - Staining, ASTM C 641

Results of Laboratory Tests for SLA Concrete Mixes Made Without Sand. Exploratory laboratory studies were conducted using SLA to make lightweight concrete without sand in order to evaluate its potential as a structural aggregate as per ASTM C 330. However, the resulting concrete was expected to be much lighter and hence lower in strength than that required by ASTM C 330. These tests were performed using three levels of cement. The results are summarized in Table 22. The following problems were experienced with these tests, with the exception of Test 4:

- The lack of fines made the concrete mix too coarse and hence unworkable.
- Due to the lack of fines the water separated from the mix.
- The product unit weights, in the range of 67-70 lb/ft^3, were much lower than the target values of 100-110 lb/ft^3.
- The 28-day compressive strength values were in the 843-1877 psi range, far lower than the target of 2500 psi.

Therefore, production of structural concrete by formulating lightweight concrete mixes using SLA without sand was rejected for further consideration. This constraint was necessary due to the fact that the SLA produced in the pilot program was devoid of fines as they were screened out and used to make pelletized SLA.

Table 22. Use of SLA for Structural Lightweight Concrete Without Sand

Test No.	Aggregate Type, Application and Unit Weight		Cement Sacks/yd³	W/C Ratio	Slump in.	Air %	Product Unit Weight lb/ft³	Compressive Strength psi*	
	Application per ASTM C330	lb/ft³						7-day	28-day
1	SLA as 3/8" combined	51.3	5½	0.6	0	3.8	66.9	375	843
1A	SLA as 3/8" combined	51.3	5½	0.65	0.5	4.8	67.4	610	963
2	SLA as 3/8" combined	51.3	6	0.65	0.75	4.8	69.6	740	1877
3	SLA as 3/8" combined	51.3	6½	0.65	1.25	4.8	69.9	1180	1840
4	Commercial LWA (3/8" combined)	53.8	6	0.65	1.5	3.9	70.0	-	2370

*Average of three tests.

Results of Laboratory Tests for Various LWA Concrete Mixes Using Sand. The results of laboratory studies to make lightweight concrete mixes using SLA, LWA, and sand mixes are summarized in Table 23.

SLA as 3/8" combined aggregate. Tests to evaluate SLA as 3/8" combined aggregate (produced from 1/4" x 50M Slag I), using 6 sacks of cement/yd^3 of concrete, resulted in 7- and 28-day strengths for the SLA concrete of 1120 and 1750 psi respectively (Test 2199). The unit weight of the concrete was 107 lb/ft^3. The 28-day compressive strength of the 3/8" combined commercial LWA (control sample) was 2400 psi at a unit weight of 115 lb/ft^3. Neither of these aggregates met the ASTM C 330 requirement of a compressive strength of2500 psi at 105 lb/ft^3.

Since the SLA concrete 28-day strength failed to meet the ASTM strength requirement, additional tests were performed using 6.5 sacks of cement/yd^3 concrete, and the results are reported in Table 23. At the higher cement level, the 28-day strength was 2070 psi at 107 lb/ft^3 which is still considerably lower than the ASTM requirement. The 28-day strength results of the commercially produced LWA at 3440 psi and 112 lb/ft^3 (control test 2206) were much higher than those of the SLA concrete and met the ASTM requirement at the given unit weight level. It was concluded that the strength of the SLA concrete could be increased by further work to control the fines content.

Table 23. Evaluation of SLAs for Sand-Lightweight Concrete Application

Test No.	Aggregate Type, Application and Unit Weight: Type and Application per ASTM C330	Aggregate Type, Application and Unit Weight: lb/ft³	Sand*/ Aggregate	W/C Ratio	Slump in.	Air %	Unit Weight lb/ft³	Comp. Strength, psi: 7-day**	Comp. Strength, psi: 28-day
Tests Using 6.0 sacks of cement/yd³									
2205-A	Commercial LWA (5/8" and 3/4" coarse)	36.0	48/52	0.65	4.0	3.5	119.6	-	-
2205	Commercial LWA (3/4" coarse)	38.0	36/64	0.43	3.5	2.0	112.8	2380	3400
2201	Commercial LWA (3/8" combined)	53.8	45/55	0.65	3.5	4.0	114.8	1500	2400
2199	SLA as 3/8" combined	51.3	43/57	0.65	4.0	3.0	106.7	1120	1750
2208	Commercial LWA as 5/8" coarse	34.0	41/59	0.46	2.5	2.0	113.8	2420	3390
2207	Commercial LWA as 5/8" coarse	34.0	39/61	0.46	2.0	2.0	108.6	2220	3240
2209-A	Clay LWA as 3/4" coarse	48.9	54/46	0.52	7.0	--	115.4	***	***
2209	Clay LWA as 3/4" coarse	48.9	49/51	0.45	3.0	1.0	114.8	3430	4800
2211	50/50 SLA as 3/4" coarse	40.9	44/56	0.48	2.5	2.0	112.3	2910	4210
Tests Using 6.5 sacks of cement/yd³									
2200	SLA as 3/8" combined	51.3	43/57	0.65	4.0	3.8	107.0	1350	2070
2206	Commercial LWA as 5/8" coarse	34.0	37/63	0.43	2.0	2.0	111.8	2730	3440
2210-A	Clay LWA as 3/4" coarse aggregate	48.9	48/52	0.42	3.5	1.0	115.2	***	***
2210	Clay LWA as 3/4" coarse aggregate	48.9	46/54	0.42	3.5	1.0	114.3	4040	5100
2212	50/50 SLA as 3/4" coarse aggregate	40.9	45/55	0.44	3.25	2.0	114.7	3480	4360

*Sand unit weight was 102 lb/ft³, 99% passing 4M, 1.9% passing 200M (dry).
**Average of three tests.
***Test specimen exceeded 115 lb/ft³.

50/50 SLA as 3/4" coarse aggregate: Tests conducted with 50/50 slag/clay aggregates using 6.0 sacks of cement/yd³ concrete resulted in 7-day and 28-day concrete strength measurements of 2910 and 4210 psi respectively. The 28-day value exceeds the ASTM requirement of 4000 psi at a unit weight of 115 lb/ft³. These results were far superior to those of tests done using SLA (3/8" combined) at the same cement level, as well as to control Test 2205 using commercially manufactured aggregates which had a 28-day strength value of 3400 psi.

The tests conducted at the higher (6.5 sacks/yd³ concrete) cement level resulted in compressive strengths of 3480 and 4380 psi for the 7- and 28-day curing periods, respectively (Test 2212), at a unit weight below 115 lb/ft³. The control test strengths using clay LWA (Test 2210) were 4040 and 5100 psi, which are in a comparable range. The 28-day compressive strength of the concrete using commercial LWA at the 5/8" size designation was 3440 psi, which is lower than that resulting from use of the SLA/clay-based aggregate. These data indicate that blending expanded slag and clay results in a high-quality product. It was concluded that 50/50 SLA as ¾" coarse aggregates with clay LWA would make an acceptable structural concrete using 6 sacks of cement/yd^3 concrete.

Freeze/Thaw Testing of SLA Concrete. In order to assess the durability of the structural concrete made from SLA, sand and cement ASTM C 66, Procedure B was performed on the specimens. The test subjected the samples to the stress of repeated freezing and thawing.

The mix designs were the same as previously used to produce sand and SLA-based cement concrete specimens:

- Mix 2211R prepared using 3/4" SLA made from 50/50 slag/clay blend
- Mix 2205R prepared using 5/8" and 3/4" LWA made from clay.

The 28-day compressive strength of the SLA concrete specimen (with 6.0 sacks of cement/yd^3 concrete) was 3000 psi at 114.7 lb/ft^3, which is below the ASTM requirement of 4000 psi at a unit weight of 115 lb/ft^3. However, some specimens using slightly different sand-to-aggregate ratios but the same cement content had compressive strength values of over 4000 psi at unit weights below 115 lb/ft^3.

In order to determine the aggregate properties without an entraining agent, freeze/thaw tests were conducted for the two mixes without air entrainment. Test specimens were saturated for a period of four hours at 40°F prior to the start of the test. The results are shown in Table 24. They indicate that the specimens exhibited cracking as a result of freeze/thaw stresses after 64 cycles. At cycle 98, cracking was severe. Due to specimen deterioration, the fundamental transverse frequency could not be measured, thus precluding calculation of the relative dynamic modulus of elasticity. It is hypothesized that the cracking was due to the following reasons:

- The lower density of the SLA with a higher proportion of pores and higher moisture retention capacity
- The absence of an air-entraining agent in the concrete, which typically helps improve freeze/thaw performance.

Table 24. Resistance of Concrete to Rapid Freeze/Thaw (ASTM C 666, Procedure B)

Specimen		Number of Freeze/Thaw Cycles							
		0	32	64	98	0	32	64	98
		Mix 2205-R (1)				Mix 2211-R (2)			
1	Relative dynamic modulus of elasticity, %	--	100	76	--	--	(3)	(3)	(3)
	Weight, gm, SSD	5456	5460	5491	--	6063	6072	6098	--
	Weight change, gm	0	+4	+35	--	0	+9	+35	--
2	Relative dynamic modulus of elasticity, %	--	98	67	--	--	(3)	(3)	(3)
	Weight, gm, SSD	5492	5518	5547	--	6053	6069	6119	--
	Weight change, gm	0	+26	+55	--	0	+16	+66	--
3	Relative dynamic modulus of elasticity, %	--	96	64	--	--	(3)	(3)	(3)
	Weight, gm, SSD	5576	5698	5729	--	6043	6060	6100	--
	Weight change, gm	0	+122	+153	--	0	+17	+57	--
Average	Relative dynamic modulus of elasticity, %	--	98	69	--	--	(3)	(3)	(3)
	Weight change, gm	0	+51	+81	--	0	+14	+53	--

(1) Mix 2205R: Control mix using expanded clay LWA at 35.3 lb/ft^3, which made concrete with a compressive strength of 3400 psi and unit weight of 112.8 lb/ft^3.

(2) Mix 2211-R: 505/50 slag clay expanded to 39 lb/ft^3, which made concrete with a unit weight of 114.8 lb/ft^3.

(3) Due to specimen deterioration, the fundamental transverse frequency could not be measured, thus precluding calculation of the relative dynamic modulus of elasticity.

It was concluded that further testing and development was needed to overcome the freeze/thaw problem.

2.3.4 Laboratory Evaluation of SLA for Insulating Concrete Application

Insulating concrete is applied in a layer on the flat roof surfaces of buildings to increase their insulating properties, particularly in warehouses located in climate zones that experience temperature extremes. Another application for insulating concrete is in making concrete panels used to improve the insulating properties of building walls. Insulating concrete is made using two materials: expanded perlite and expanded shale. ASTM C 332 provides specifications for LWA for insulating concrete applications. Three properties of importance are the unit weight, compressive strength, and thermal conductivity of the concrete. In testing the suitability of SLA for use in making insulating concrete, these three properties were measured and compared with those of conventional insulating concretes made from expanded perlite and expanded shale.

SLA with a unit weight of 26 lb/ft^3 produced using the fluidized bed expander was screened according to ASTM C 332. In order to evaluate SLA for use as an aggregate in insulating concrete, specimens were made in order to test their compressive strength and thermal properties. Using the mix proportions for perlite insulating concrete re-roofing material as a guide, 2" cubes and a 12" x 12" x 1" slab were made using 3/8" x 0 expanded slag according to the following formula:

Type I cement:	800 g
3/8" x 0 expanded slag:	4 times cement by volume
Water:	640 g
Air-entraining agent:	8.3 g
10 mm polypropylene fibers:	8 g

These samples were mixed according to ASTM C 109 and cured in a 98% relative humidity chamber at 25°C. After 7 days, the cubes were removed for testing of their compressive strength. The highest 7-day compressive strength achieved was 1750 psi, and the unit weight of the samples was approximately 51 lb/ft^3, which is lower than expected values.

The 12" x 12" x 1" slab was tested for its thermal conductivity. The typical thermal conductivity of perlite (Group I) is 0.45-1.5 Btu-in/hr-ft^2-°F, and that of shale-based aggregates (Group II) is 1.5-3.0 Btu-in/hr-ft^2-°F. As may be seen in Table 25, the thermal conductivity of the SLA concrete at 0.984 Btu-in/hr-ft^2-°F is much lower (i.e., better) than that of Group II shale aggregates and falls within the Group I range. The expanded slag therefore, is an excellent insulator suitable for use in making insulating concrete panels.

Table 25. Apparent Thermal Conductivity and Thermal Resistance of SLA Test Specimens

Material	Concrete Unit	Thermal Conductivity		Thermal Resistance
	Wt, lb/ft^3	W/m-K	Btu-in/hr-ft^2-°F	hr-ft^2-°F/Btu
SLA, 26 lb/ft^3	45.1	0.142	0.984	0.93
Perlite	15-50	0.065-0.22	0.45-1.5	-
Shale	50-90	0.22-0.43	1.5-3.0	-

Note: The SLA tests were conducted at 25°C whereas the reference data are at 24°C.

2.3.5 Laboratory Evaluation of SLA for Loose Fill Insulation Application

Typically, the outer walls of commercial buildings are made with masonry blocks. The cavities or air gaps in the blocks are filled with expanded perlite to improve the building insulation. The cavity between the block wall and brick layer, if any, is also filled with expanded perlite. ASTM C 549 provides specifications for using expanded perlite as a loose fill insulating material. The key properties of interest are the degree of insulation provided, light weight, lack of dustiness, and lack of moisture absorption. Expanded slag produced using the fluidized bed expander was screened according to ASTM C 549 for use as loose fill insulation. The SLA sample had a unit weight of 29 lb/ft^3 and a thermal resistance of 1.46 hr-ft^2-°F/Btu. This is higher than the value of 2.4 hr-ft^2-°F/Btu for the 11 lb/ft^3 unit weight perlite, as shown in Table 26. However, expanded slag is much easier to work with due to its significantly lower degradation characteristics and may also be easier to apply.

Table 26. Thermal Conductivity and Thermal Resistance of SLA for Loose Fill Insulation

Material Type	Unit Weight	Temperature	Thermal Conductivity		Thermal Resistance
	lb/ft³	°C	W/m-K	Btu-in/hr-ft²-°F	hr-ft²-°F-Btu
Expanded slag	29	25	0.093	0.645	1.46
Perlite	7.4-11	24	-	-	2.6-2.4

It was concluded that SLA does not offer the same degree of thermal resistance as does expanded perlite. Therefore, SLA may not be a good substitute for expanded perlite unless its unit weight can be lowered significantly.

2.3.6 Laboratory Evaluation of SLA in Horticultural Applications

Expanded perlite, vermiculite and peat moss are used by nurseries in potted plants, shrubs, and trees. These materials improve soil porosity which helps develop a strong root structure, and also improve water retention. Of these, the most expensive materials are expanded perlite and vermiculite. Expanded slag was therefore tested as a partial or complete substitute for these two materials in horticultural applications. It was anticipated that the higher density of SLA would have a favorable impact on the durability of potting mixes used in large plants and field applications. This test work was done at a commercial nursery which was selected based on their expertise in this field, the unique techniques they employ to control the supply of nutrients, and their willingness to test a new material.

Three batches of SLA were used for this test work, along with a standard perlite mix and a soil mix. The topsize and unit weight of the SLA used for this work is given below:

- Sample A: 1/4" topsize and unit weight of 35-40 lb/ft³
- Sample B: 1/4" topsize and unit weight of 20-30 lb/ft³
- Sample C: 1/4" topsize and unit weight of <20 lb/ft³
- Control 1: Perlite/vermiculite mix
- Control 2: Typical soil mix

The evaluation consisted of observation of the growth rate, general health, and appearance of tomato plants grown in a solarium. For this purpose, a number of potting mixes measuring approximately 1 cubic yard were prepared using expanded slag as a partial or total substitute for perlite and vermiculite which are added to improve porosity and water retention.

As may be seen in Table 27, the initial weight of the three SLA samples (6.75-10.5 lb) used to fill the flats was considerably higher than that of the other materials. Also, the maximum moisture content under full saturated conditions (19-29%) was considerably lower than that of the other materials. The customary frequency of watering and fertilizer addition was followed. This approach allowed comparison of water and fertilizer retention capacity. Plant growth was measured over a period of 20 days between 8 July 1997 and 28 July 1997, and the general condition of the plants reported. For the three samples, the best results were obtained for Sample

B, where only one plant wilted during the entire period. In the case of Sample A, five plants wilted, while for Sample C, seven plants wilted. This trend does not seem to follow the moisture retention capability of the three samples of expanded slag. While the reason for this is not fully understood at this time, the data indicate that SLA may be used as a partial substitute for conventional nursery materials.

Table 27. Evaluation of Expanded Slag in Supporting Plant Growth

	SLA Sample A	SLA Sample B	SLA Sample C	Vermiculite	Perlite	Soil Mix
Unit wt, lb/ft^3	35-40	20-30	<20	-	-	-
Dry wt, lb	10.5	9.5	6.75	4.25	4.0	5.5
Wet wt, lb	13.0	12.25	9.0	13.0	9.25	11.5
Water retention, lb	2.5	2.75	2.75	8.75	5.25	
Max. moisture content, wt%	19	22	29	67	57	52
Water retention, lb/100 lb	24	29	41	206	131	109
7/8/97	Planted and watered all flats					
7/14/97	Fertilized all flats with CalMag 15-5-15					
7/15/97	Measured height and condition of plants					
Height, inches	1	1¼	1¼	1¾	1½	1¾
No. of plants that died*	5	0	4	0	0	0
7/16/97	Fertilized (20-10-20) vermiculite, perlite, and soil mix flats					
7/21/97, height (inches)	1½	1¾	1¾	3¾	2¾	3¾
No. of plants that died*	5	0	4	0	0	0
7/22/97	Fertilized all flats with 20-10-20					
7/28/97, height (inches)	3	2¾	2½	7	7	8
No. of plants that died*	5	1	7	0	0	0

*Out of 18 plants per flat.

The following conclusions were drawn from these tests:

- SLA can be used as a partial substitute for conventional potting materials.
- The moisture retention capacity of the SLA needs to be improved by opening up the pores. This may be accomplished by crushing it and using a finer slag particle size.
- The low moisture retention capacity of the SLA can be accommodated provided that it is used along with materials that have a higher moisture retention capacity.

- The higher unit weight of the SLA can add stability to larger potted plants, shrubs, and trees, such as those in containers over 3 gallons in capacity. This stability is currently achieved using bark chips.

- SLA has an excellent aeration capacity.

- The pores in the SLA provides an excellent root support structure, and the superior strength of the SLA indicates that it will have a longer useful life than conventional perlite and vermiculite-based materials.

2.3.7 Evaluation of SLA in Production of Cement Panels (Waterproof Boards)

Based on evaluation of the test results for the use of SLA in making insulating concrete, another similar application was identified: production of lightweight cement concrete panels used in the construction of bathrooms and other areas where walls are exposed to moisture. This is a relatively new but fast-growing application that requires 35-45 lb/ft^3 aggregates. These cement panels are used to ensure a waterproof, smooth and very stable surface for the application of ceramic tiles. Praxis contacted a manufacturer and sent samples of SLA I to them for laboratory evaluation. Exploratory tests indicated that SLA could be used as a substitute for conventional lightweight aggregates to make these panels. Two 55-gallon drum samples of 10 x 50M SLA III were supplied to the manufacturer, along with cyclone fines. One of the drums contained 35-40 lb/ft^3 SLA, and the other contained 40-45 lb/ft^3 SLA.

A Praxis engineer visited the manufacturer's laboratory to discuss material requirements and provide the results of earlier tests. The laboratory completed an initial evaluation of the SLA and found the material satisfactory.

In addition, we conducted exploratory tests in a commercial laboratory on the use of expanded slag for the panel application. The test product showed excellent potential due to the low product unit weight and excellent workability imparted by the unique slag particle shape.

In testing the suitability of expanded slag for use as panels, a 1:4 ratio of cement to coarse slag was used, without additives. Fine slag was added to adjust the unit weight and to improve the particle size distribution of the mix. Specimen bars (1" x 1" x 12") were cast and cured in a moist environment. After 3 and 7 days, the bars were removed and tested for Modulus of Rupture per ASTM C-293 using a 3-point bend test. The mix design used and results are given in Table 28.

Table 28. Mix Design and Modulus of Rupture Test Results for SLA in Panel Application

Mix Design	**Quantity**
Type I cement, g	150
Coarse slag, g	600
Fine slag, g	200
Water, g	200
Strength Evaluation	
Unit weight, lb/ft^3	78.27
Modulus of Rupture (ASTM C 293), psi	
3-day	171.0
7-day	178.1

The 3-day flexural strength of 171 psi compares well with the minimum value of 100 psi for autoclave cellular concrete used for the production of wallboard.

The unit weight of the current sample equates to 3.26 lb per 12" x 12" x 1/2" piece, which is almost identical to the target weight of 3.2 lb. In order to improve upon the flexural strength of this material, the cement-to-aggregate ratio or the ratio of coarse to fine sand may be increased.

It was concluded that SLA may be used in making cement panels. As was the case with the roof tile application, the flexural strength of wall panels made from SLA would be improved by optimizing the particle size distribution, the use of chemical additives, and the addition of cement.

2.4 Economic Analysis Of Expanded Slag Production And Utilization (Task 2.4)

The objective of this task was to develop cost estimates for commercial production of slag lightweight aggregates (SLA) and to study the process economics. Two approaches were used in this evaluation:

- The economics of SLA production was compared with slag disposal.
- The economics of SLA production was evaluated with respect to the estimated market value of end products.

The comparative evaluation with respect to the costs of disposal involved establishing the disposal costs of slag based on experience with similar wastes such as fly ash. The avoided costs of disposal were then compared with the costs of producing SLA. The premise was that the slag could be pyroprocessed and then given away as an alternative to disposal. However, since the costs of SLA production were considerably higher than the avoided costs of disposal, pyroprocessing could not be justified as an alternative to disposal.

The second evaluation involved establishing the economics of SLA production and utilization using the estimated market price of the expanded slag. For this assessment a market survey was conducted to establish the regional prices of conventional LWAs and ULWAs. These data were used to establish the prices that the slag products could command in each application. This evaluation took into consideration the fact that slag is a new material and would be expected to command lower prices even if it performed better than the conventional applications. The projected prices were then used to develop the economics as discussed in this section.

Estimation of the costs of expanded slag production involved developing a process flowsheet based on pilot plant operations data generated during the project, compilation of a list of process equipment needed for physical and pyroprocessing of slag to produce marketable lightweight aggregate products, and development of equipment-factored capital cost estimates. Two sizes of SLA production plants were considered in this study, as described below:

- A plant to process slag generated from a gasifier facility with a 200-MW equivalent capacity. Such a facility typically uses 2,000 tons/day of bituminous coal containing 10% ash. Depending upon the carbon conversion rate, this facility may generate 220 tons/day of slag containing 10% char. This approximates the size of a number of existing gasifiers in the United States.

- A plant to process slag generated from a gasifier facility with a 400-MW equivalent capacity. Such a facility would typically use 4,000 tons/day of bituminous coal containing 10% ash. Depending upon the carbon conversion rate, this facility may generate 440 tons/day of slag containing 10% char. This would approximate the feed capacity of a typical commercial LWA plant that currently uses conventional expansible clays.

The relative advantages and disadvantages of the following options were considered:

- Production of SLA at the gasifier location (on-site production)
- Production of SLA at a lightweight aggregate facility (off-site production).

Several factors, such as the need to process slag for char removal at the gasifier site and the costs of transporting slag to an off-site production facility, play a significant role in evaluating these options. It was concluded that, by and large, the SLA production facility would be more efficient if it were integrated with the gasifier operation. However, this does not preclude the sale of slag to an off-site LWA production facility which may be interested in using it as an alternative feed material to shale.

Since the commercial SLA production plant is assumed to be located "across the fence" from a gasifier facility, water and power requirements are assumed to be available at market cost at the site. The SLA production facility is envisaged to consist of two sections:

(i) Slag receiving and processing section for recovery of char, and
(ii) Pyroprocessing section for SLA production and product storage.

Coarse (+10 mesh) slag will be used to produce SLA in discrete particle form, and the fines will be used to produce extruded pellets of the desired size using a clay binder prior to expansion using the same pyroprocessing equipment. The facility includes product crushing equipment and product storage and handling bins sized in accordance with modern LWA industry practices. Major process equipment costs were estimated based on the above assumptions and used to prepare equipment-factored capital cost estimates. The capital and operating costs thus generated have an accuracy of ±25%, which is considered sufficient for conducting first-level economic assessments.

Slag expansion process energy requirements were estimated based on the pilot plant operations data generated during the project and scaled-up by Fuller Co. Labor and other costs were estimated based on industry experience.

The basic data were generated during Phase I and updated where needed in Phase II. A computer worksheet was developed and used to conduct economic evaluations of various alternative scenarios, as discussed in subsequent sections.

2.4.1 Costs of Production of LWA and ULWA Made from Expanded Slag

As a first step, the costs of production of various expanded slag products were estimated for two different sizes of commercial-scale plants. The design criteria for a plant processing slag from a 200-MW capacity gasifier are given in Table 29. Similarly, material balances were generated for the 400-MW system and are provided in the same table.

Table 29. Design Criteria for Plant to Process Gasifier Slag

Criteria	200 MW	400 MW
Coal usage, t/d	2000	4000
Coal ash, %	10	10
Plant operation, days/year	365 @ 90% availability	365 @ 90% availability
Slag generated, t/d	220 (72,270 t/y)	440 (144,540 t/y)
Prepared slag quantity, t/d	161.3 (52, 987 t/y)	322.6 (105,974 t/y)
Char primary concentration, t/d	58.7	117.4
Char concentration (fuel), t/d	17.6	35.2
Reject slag (disposal), t/d	41.1	82.2

*see description below.

The reject slag, which has a high char content, is assumed to be a disposal stream for purposes of SLA production in this evaluation. However, this stream can be processed further to remove the char fraction from it. The remaining fine slag could then be used with the rest of the minus 10-mesh fines to prepare extruded pellets.

The following assumptions were made in projecting SLA production costs:

- Expanded slag products with unit weights ranging between 20 and 50 lb/ft^3 would be produced by controlling the expansion temperature. SLA product densities would be targeted to match the requirements of most LWA applications and selected ULWA applications.

- Fuel requirements for the two sizes of plants, as estimated by the kiln designer, are given in Table 30. The char recovered from the slag is assumed to provide 50% of the fuel requirements for pyroprocessing using a rotary kiln. In a fluidized bed system, the char would provide up to 80% of the fuel requirements.

Table 30. Fuel Requirements for Various Case Studies

Case	Slag Feed (t/d)	Fuel	Fuel Rate (Million Btu/ton of feed)	Btu from Char (%)
A1: Small rotary kiln	220	Coal & char	2.32	50
A2: Large rotary kiln	440	Coal & char	1.80	50
B1: Small fluidized bed	220	Bunker C oil & char	2.50	80
B2: Large fluidized bed	440	Bunker C oil & char	2.50	80

- Coal is the preferred fuel for a rotary kiln system because it is relatively cheap and readily available at the gasifier site. The cost of 11,500 Btu/ton of coal delivered to the site is assumed at $30/ton or $1.30/MBtu. Oil would be the preferred fuel for a fluidized bed expander system. The cost of Bunker C oil is assumed at $2.80/MBtu.

- A plant useful life of 20 years is assumed, and straight-line depreciation is used in assessing plant capital expenses.

- Plant capital costs are allowed a contingency of 15%.

- The cost of borrowing capital is assumed at 8%, and interest expenses are applied to operating costs.

SLA-Based Lightweight Aggregate Production Costs Using a Rotary Kiln. Based on the assumptions given above, SLA production costs were compiled for two plant sizes for both the rotary kiln and fluidized bed pyroprocessing methods. Table 31 provides estimated costs for production of SLA at 220 t/d and 440 t/d feed capacity respectively using similar (rotary kiln) processing systems. The table also provides current conventional LWA production costs which were compiled based on a survey of four plants. The costs compiled for the slag processing plant assume that the necessary capital is borrowed at 8% interest.

As may be seen in the table, the cost advantages for the SLA production operation are provided by (i) lower overall energy requirements due to the lower temperature of expansion, (ii) the ability to use char as a fuel in the kiln to meet 50% or more of the total energy requirements, and (iii) the absence of shale mining costs. The disadvantages are: (i) high interest on capital expenses and (ii) the inability to take advantage of economies of scale in a 220-t/d operation. However, a larger plant servicing the output of a 400-MW capacity gasifier would be able to use a large rotary kiln of a comparable size to those used in most commercial LWA operations.

Table 31. Comparative Costs of Kiln Production of LWA vs. SLA

Cost Item	Current Method Using Shale, $/ton(1)	SLA $/ton(2)	SLA, $/ton(3)
System type	Large rotary kiln	Small rotary kiln (A1)	Large rotary kiln (A2)
Fuel	Fuel Oil	Coal & char	Coal & char
Mining and preparation	6.00	-	-
Transport ore to plant	0.50	-	-
Processing Costs			
Clay binder	-	1.45	1.45
Labor (O&M)	6.23	7.50	6.25
Fuel	5.09	2.12	1.64
Power	1.37	1.35	1.35
M&S	1.85	1.94	1.48
Other	1.11	1.10	1.10
Overhead	2.24	-	-
Depreciation	5.71	5.62	4.28
Interest on capital	Unknown	8.99	6.85
Total product costs	30.10	30.07	24.40

(1) Fuller survey of four U.S. LWA plants; mining costs added later.
(2) Praxis/Fuller estimate for 220-t/d raw slag system.
(3) Praxis/Fuller estimate for 440-t/d raw slag system.

SLA-Based Ultra-Lightweight Aggregate Production Costs Using a Fluidized Bed Expander. In Table 32, the estimated costs for producing ULWA from slag using the fluidized bed method are presented alongside those for conventional ULWA production. The fluidized bed expander manufactured by Fuller Co. was used as it provides improved control of the product unit weight. The estimated cost of production of conventional ULWA is based on information provided by a leading manufacturer of expanded perlite. The cost advantages for the SLA operation are similar to those described in the section above. The disadvantages include the inability (thus far) to produce a true ultra-lightweight product (that is, unit weight in the 4-12 lb/ft^3 range) from slag. However, we have produced expanded slag products with unit weights as low as 16-18 lb/ft^3, and it is assumed that further reduction is achievable with more testing and development work.

In comparing the production costs of expanded slag with those of expanded perlite, a volumetric correction may need to be applied to the slag because it has a considerably higher unit weight in lb/ft^3. As may be seen in the above table, the production costs of expanded slag would be lower than those of conventional perlite-based ULWAs. In addition, the equivalent SLA product has a higher strength which can provide many advantages.

Table 32. Comparative Costs of Producing ULWA vs. SLA

Cost Item	**Current Method Using Perlite \$/ton**	**SLA, \$/ton 16 lb/ft^3**	**SLA, \$/ton 16 lb/ft^3**
Processing method	Vertical shaft furnace	Small fluidized bed (B1)	Large fluidized bed (B2)
Mining and preparation	40.00	-	-
Shipping ore to plant	40.00	-	-
Processing Costs			
Binder for fines	-	1.45	1.45
Labor	12.00	7.50	6.25
Fuel	8.00	1.34	1.29
Power	4.50	1.35	1.35
M&S	3.00	1.70	1.29
Other, loading	2.00	1.10	1.10
Overhead	10.00	-	-
Depreciation	4.75	4.63	3.52
Interest	Unknown	7.41	5.63
Total product costs	124.25	26.48	21.87
Costs after volumetric correction	124.25	52.96	43.74

The assessments in the tables above indicate that the production costs for SLA are generally comparable to or lower than those for conventional LWAs, depending upon economies of scale. SLA production costs would be considerably lower with larger-scale production.

With regard to ULWAs, production costs of comparable SLA products are estimated to be significantly lower than those for conventional materials provided that the higher product densities of slag-based ULWA are acceptable. Even if a 2-to-1 correction factor is applied for the higher density of expanded slag (which necessitates use of a larger quantity for the same volumetric fill), slag-based ULWA is far cheaper to produce than the conventional products.

2.4.2 Market Assessment of Conventional LWA and SLA

The objectives of this subtask were to obtain an initial assessment of the market value of various conventional LWA products targeted for substitution by slag and to estimate the market value of the corresponding products if they were made from expanded slag. The market value of LWA is used to estimate the projected value of the SLA taking into account its quality and performance relative to the conventional materials. As a first step, various trade associations and major users of LWA and ULWA were contacted to obtain price structures and marketing information. Contacts with these organizations allowed us to gauge accurately the current sale prices of various aggregates. The organizations contacted included:

- Expanded Shale, Clay and Slate Institute
- Perlite Institute
- National Concrete Masonry Association.

Conventional Lightweight Aggregate Production, Costs, and Markets. Development of a market assessment for SLA included identification of the current market for conventional LWAs and ULWAs and specific applications for which SLA would be an acceptable substitute. According to U.S. Bureau of Mines data, shown in Table 33, production and consumption of lightweight materials was 7.6 million tons in 1991, including expanded shale production of 3.96 million tons. These products are typically sold for \$35-\$50 per ton. The current annual production of lightweight and ultra-lightweight materials is estimated at 10 million tons. This excludes fly ash, which has a unit weight of 70 lb/ft^3 and is also used as a medium lightweight material.

Consumption and production of these materials is greatly dependent on production and transportation costs. Therefore, if cheaper by-product materials could be used to produce these products, especially at lower energy requirements, consumption would be significantly increased.

Table 33. U.S. Production of Expanded Shales, Clays, and Volcanic LWAs

Mineral	1990	1991
Shales and clays, million yd^3	18.58	17.6
Shales and clays, million tons	4.18	3.96
Pumice, pumicite, million tons	0.487	0.441
Volcanic cinders, scoria, million tons	3.2	3.2
Total, million tons	7.87	7.6

Conventional Ultra-Lightweight Aggregate Production, Costs, and Markets. Conventional ULWAs have unit weights in the range of 4-12 lb/ft^3 and are produced by thermal expansion of perlite and vermiculite ores at temperatures of 1600-2000°F. Their low unit weight and thermal conductivity (as low as 0.35 Btu-in/h-°F at a loose weight of 2.5 lb/ft^3) make ULWAs ideal insulating materials for loose fill insulation and aggregates for the manufacture of insulating concrete and numerous other insulation applications. Other applications for expanded perlite include filtration media, industrial fillers, abrasive in cleaners and polishes, soil amendment for horticulture, carrier of chemicals for pesticides and fertilizers, and acoustic material.

U.S. Department of the Interior production and consumption figures for expanded perlite and vermiculite are given in Table 34. The actual domestic consumption of perlite ore in 1991 was 595,000 tons, which takes into account the import of 60,000 tons and export of 32,000 tons. The drop in production in 1991 is related to increased prices and softening demand due to a decline in industrial and commercial construction activity. The total market value of the 498,000 tons of finished products made from expanded perlite was \$101,695,000 or \$204 per ton. Expanded perlite typically retails at \$2.00/ft^3, which corresponds to \$500/ton based on an average unit weight of 8 lb/ft^3 for the expanded products. The consumption of these materials is also highly sensitive to their costs of production; the availability of low-cost alternative feedstocks such as slag could increase the consumption of these materials.

Table 34. U.S. Production of Perlite and Vermiculite

Mineral	1988	1989	1990	1991
Perlite, tons	576,000	601,000	635,000	567,000
Vermiculite, tons	304,000	275,000	230,000	185,000
Total ULWA raw material, tons	880,000	876,000	865,000	752,000

Economics of Production of ULWA from Slag. Slag has been demonstrated to produce an expanded aggregate, which may be used as a substitute for ultra-lightweight aggregates (ULWA) for some applications. The technical and economic advantages of producing ultra-lightweight aggregates from slag include the fact that, being a waste material, it is available at no or low cost. Prepared perlite ore, in contrast, sells at $80 per ton, which includes the high costs of transportation from New Mexico to various production facilities. In contrast, no mining costs are involved for slag, energy requirements for expansion are lower than those for perlite expansion, and avoided disposal costs may be a major factor favoring its utilization.

Assessment of Market Price of SLA. In order to estimate sale prices of SLA for use in making various end products, we contacted manufacturers to conduct a market survey of the prices of structural LWAs by region and by application. The prices varied considerably by region, as indicated in Table 35.

Table 35. Typical Regional Prices of Lightweight Aggregates

Location	$/yd^3	$/ton
East coast	17.00	25.00
Midwest	20.00	30.00
West coast	30.00	44.00
Average	22.33	33.00

Prices also varied for each application due to factors such as quality and product size preparation. Based on the above, typical prices quoted for major applications are given in Table 36. Based on our experience, we estimated the price that the SLA would command in each application. The estimated SLA prices, along with the slag fraction that would be used to produce it, are given in the same table.

Table 36. Estimated Market Prices for LWAs, ULWAs, and SLA by Application

Application	LWA Price ($/ton)	SLA Price ($/ton)	SLA Product
Lightweight Aggregates			
Block aggregate	37.00	30.00	10 x 50M SLA
Structural concrete	45.00	35.00	Extruded fines
Roof tiles	50.00	40.00	Extruded fines
Ultra-lightweight Aggregates			
Expanded perlite	150.00	40.00	+10M SLA

Since a new, unproven product would command a lower price, the sale prices for SLA aggregates were established at $30/ton for block aggregates, $35/ton for structural aggregates, and $40/ton for roof tile and ultra-lightweight aggregate applications. Using a product mix based on the percentage of coarse and fine slag, the weighted average price of SLA was estimated at $34.75/ton. This price was used for purposes of economic evaluation of SLA production.

2.4.3 Solid Waste Management Costs

The objectives of this subtask were to compile solid waste management costs for slag from a gasifier on a $/ton and $/ft^3 basis. When disposal is avoided through utilization, these costs are used as credits in the economic evaluation of expanded slag. Solid waste management costs typically include the following:

- Site preparation
- Handling and transportation
- Storage and compaction
- Land reclamation
- Runoff, drainage, and seepage monitoring.

Solid waste management costs tend to be highly site-specific due to transportation and site-related costs. Therefore, they vary considerably depending on the distance over which the solid waste has to be transported for disposal. These costs also vary on a regional basis depending on the availability of land for solid waste disposal. Thus, disposal costs in the northeastern United States are the highest due to the limited availability of disposal sites. Our information is that typical utility waste disposal costs range between $10 and $20 per ton. For purposes of this analysis, a value of $15/ton is used as the disposal cost. Since these avoided costs would provide substantial savings to the gasifier operation, this amount could potentially be made available to the slag aggregate production facility as a tipping fee per ton of slag accepted.

2.4.4 Economic Evaluation of SLA Production

An economic analysis of SLA production was conducted for two production capacities using two alternative pyroprocessing methods. The four case studies developed to study the process economics are:

- Case A1: Small rotary kiln plant for SLA production using the slag output from a 200-MW equivalent gasifier generating 220 t/d slag
- Case A2: Large rotary kiln plant for SLA production using the slag output from a 400-MW equivalent gasifier generating 440 t/d slag
- Case B1: Small fluidized bed plant for SLA production using the slag output from a 200-MW equivalent gasifier generating 220 t/d slag
- Case B2: Large fluidized bed plant for SLA production using the output from a 400-MW equivalent gasifier generating 440 t/d slag.

A computer worksheet was developed to compile the capital costs and conduct overall economic analyses for various case scenarios for the production of SLA products. The worksheet covered the following issues:

- Capital costs for slag handling, preparation, pyroprocessing, and contingencies
- Direct operating costs (operating and maintenance labor, maintenance materials, consumables, and other costs)
- Indirect costs (depreciation, interest on capital)
- Credit for avoided costs of disposal of slag
- Costs for producing SLA and impact of avoided disposal costs
- Economics (payback period and return on investment) based on market prices commanded by SLA products.

The economic advantages of SLA over conventional materials are that no mining costs are involved and pyroprocessing costs are almost identical. Since slag expands at a temperature ~400°F lower than shale, it requires 50% less energy during the thermal processing step. Adjustments were made for various items where additional costs are incurred for slag expansion. The preliminary economics of production of SLA vs. conventional LWA based on data generated during pilot kiln operation are summarized in Table 37. The data indicate that the production costs of SLA are essentially the same as those for conventional LWAs.

As may be seen in Table 37, SLA production costs for the small rotary kiln (Case A1) at $30.06/ton are close to the production costs of conventional LWAs. Being a small operation, this case does not benefit from economies of scale and would not be profitable unless the avoided costs of slag disposal are taken into account. For Case A2, the projected production costs are $24.40/ton, which is fairly competitive with production costs at typical conventional LWA plants.

Cases B1 and B2, based on the use of small and large fluidized bed systems respectively, would be considerably more competitive because of lower capital and operating costs. Therefore, such systems should be considered for commercial SLA production, especially for lower-capacity plants. The economics for the larger-sized plant (B2) are especially attractive if the avoided costs of slag disposal are taken into account, as indicated by the payback period of under three years.

Table 37. Economic Analysis Summary

	Case A1	Case A2	Case B1	Case B2
Pyroprocessing System	Small rotary kiln	Large rotary kiln	Small fluid bed	Large fluid bed
System fuel	Coal/char	Coal/char	Bunker C/char	Bunker C/char
Slag feed, t/d	220	440	220	440
Pyroprocessing feed, t/d	188	377	188	377
Fuel rate, MBtu/t	2.32	1.80	2.50	2.50
Fuel costs, $/MBtu	1.30	1.30	2.68	2.68
Fuel from char, %	30	30	80	80
Capital costs, $	6,960,375	10,600,000	5,735,625	8,700,000
Pyro throughput, t/y	61,921	123,841	61,921	123,831
Direct O&M costs, $/t	15.46	13.27	14.44	12.73
Indirect costs (depreciation & interest), $/t	14.61	11.13	12.04	9.14
Total SLA production cost, $/t	30.07	24.40	26.48	21.87
Avoided disposal credit, $/t	-14.23	-14.23	-14.23	-14.23
Net SLA production cost, $/t	15.83	10.17	8.89	7.64
Total sales revenues, $	2,151,106	4,302,213	2,151,106	4,302,213
Projected gross margin, $/y	1,119,200	2,956,143	1,341,312	3,270,074
Average sale price, $/t	34.74	34.74	34.74	34.74
Projected gross margin, $/t	18.91	24.57	25.85	27.10
Payback period, years	6.2	3.6	4.6	2.7
Return on investment, %	16.1	27.9	23.4	37.6

Note: All capital costs and prices are given in 1996 dollars.

2.5 Separation of Char from Slag from Tampa Electric IGCC Plant (Task 2.5)

The slag from entrained-flow coal gasifiers typically contains 15-25% carbon, termed char. Char originates from the unconverted carbon in the coal. The presence of carbon in the slag is a major hindrance to its utilization. Praxis has demonstrated that slag generated from entrained-flow gasifiers can be processed to remove its char content, thus producing a carbon-free slag which can be used in a number of high-volume applications such as aggregate in cement concrete and road construction and high-value applications such as feedstock for lightweight aggregate production. The recovered char may be blended with coal and utilized as a fuel for power generation or recycled to the gasifier.

DOE added a task to the existing contract to demonstrate the applicability of the char separation process developed by Praxis to the slag generated at Tampa Electric Company's (TEC) Polk Power Station IGCC facility. This 250-MWe facility, co-funded by DOE, was installed under Round III of the Clean Coal Technology Demonstration Program.

The major objectives of the study were to:

- Test the TEC slag for char removal (Subtask 2.5.1)
- Develop a conceptual design for a char separation facility (Subtask 2.5.2)
- Develop the economics of clean slag production at TEC (Subtask 2.5.3)

2.5.1 Laboratory Testing of TEC Slag for Char Removal

An "as generated" slag sample weighing approximately ½ ton (two 55-gallon drums) was procured from the TEC IGCC plant to test its performance using Praxis' char separation process. The feed sample was analyzed at 68.4% ash (or 31.6% carbon). Please note that this char content is somewhat higher than normal as the facility was undergoing commissioning and testing when the sample was obtained. The slag generated during normal operations has a lower carbon content of ~20% as subsequently reported by plant personnel.

The Praxis slag/char separation process consists of five processing steps:

1. Screening and Recovery of Char-Free Slag
2. Gravity Separation of Slag and Char
3. Reprocessing of Char to Upgrade its Carbon Content (to achieve a user-specified char grade)
4. Dewatering of Slag Product. The recovered slag product can be dewatered using mechanical dewatering equipment and reduction of moisture through natural drainage in bins or storage piles. This would achieve product moisture levels corresponding to typical commercially available wet-screened aggregates.
5. Handling of Recovered Char Product. Since the recovered char is assumed to be recycled to the gasification process, it does not need to be dewatered but can be retained in slurry form and mixed with the new coal feed to the wet grinding circuit.

There is also an optional step (3A) to further reduce the residual char content in the clean slag.

The TEC slag sample was processed using the 400-lb/hour pilot plant set up to process the 20-ton slag sample for the main project. Two product fractions were produced:

- A char-free (clean) slag fraction
- A char fraction (primary char) containing ~35-40% ash (or 65-60% carbon).

Subsequently, the char fraction was reprocessed to upgrade its carbon content (Step 3). Table 38 presents the results for the three stages of processing. As may be seen, 14.8% of the material containing essentially no carbon was recovered in the screening step. This step, which reduced the amount of feed material to the gravity separation unit by only a small amount, is designed primarily to prevent any coarse material from entering the separation unit.

In the gravity separation step, 31.4% of the feed material, containing no carbon (i.e., 100% ash), was recovered. This, combined with the screen fraction, accounts for a total of 46.3% of the original sample recovered in the form of saleable carbon-free slag. The remaining 53.7% of the material was mass analyzed at 59.8% carbon (or 41.2% ash).

Table 38. Results of Char Separation for TEC Slag

Step	Process	Process Feed		Char Product		Slag Product	
		Wt. %	Ash%	Wt. %	Ash%	Wt. %	Ash%
1	**Screen recovery of char-free coarse slag**						
	Screen feed basis	100.0	68.4				
	Undersize (to gravity separator)			85.2	62.9		
	Oversize (to slag product)					14.8	100.0
2	**Gravity separation**						
	Gravity separator feed basis	100.0	62.9	63.1	41.2	36.9	100.0
	Whole slag basis	85.2	62.9	53.7	41.2	31.4	100.0
1, 2	**Combined results on whole slag basis**	**100.0**	**68.4**	**53.7**	**41.2**	**46.3**	**100.0**
1, 2	*Other slag combined whole slag basis*	*100.0*	*84.9*	*30.3*	*50.3*	*69.7*	*100.0*
3	**Char screening for upgrade**			Char (O/Size)		Slag (U/Size)	
	Screen feed basis	100.0	41.2	67.2	21.2	32.8	82.0
	Whole slag basis	53.7	41.2	36.1	21.2	17.6	82.0
1,2,3	**Combined results on whole slag basis**	**100.0**	**68.4**	**36.1**	**21.2**	**63.9**	**95.0**
	Combined results if slag fines discarded	100.0	68.4	36.1	21.2	46.3	100.0
	Discarded stream (whole slag basis)					17.6	82.0
1,2,3	*Other slag combined results (whole slag)*	*100.0*	*84.9*	*21.4*	*34.1*	*78.6*	*98.8*
3A	**Flotation separation of slag fines (Projected)**						
	Flotation feed basis	100.0	82.0	13.0	25.0	87.0	90.5
	Whole slag basis	17.6	82.0	2.3	25.0	15.4	90.5
1,2,3,3A	**Combined results whole slag basis (Proj)**	**100.0**	**68.4**	**38.4**	**21.5**	**61.6**	**97.6**

Reprocessing of Char to Upgrade its Carbon Content (Process Step 3): This step is aimed at further upgrading the recovered char fraction to 70-80% carbon (or 20-30% ash). The process parameters for this step are slag-dependent and need to be established for each slag by laboratory testing. In most cases, the slag recovered from this step would be blended with the main slag stream recovered from Process Steps 1 & 2. All of the recovered slag is then dewatered in Process Step 4. The results of the char upgrade step for the TEC slag are given in Table 38 above. This step recovered an additional 17.6% material containing 82% ash (or 18% carbon). This slag, when combined with the slag fractions recovered previously, accounts for an overall slag recovery of 63.9%, containing 95% ash (or 5% carbon). This product meets TEC's target specifications for the carbon content of the slag product.

Further Reduction of Char Content (Process Step 3A): In the event that the char content of the slag product from Process Step 3 needs to be lowered further to permit its use for certain high-value applications, it can be processed by flotation, as indicated in Process Step 3A in Table 38. If this step is used, nearly zero solid waste disposal can be achieved at the gasifier plant. Praxis tested this step and the results were very encouraging. However, this line of testing was not pursued as it was not in the scope of work or requested by TEC. This processing step involves additional costs and the decision to use it can only be made after full consideration of the potential applications for which the slag and char are being prepared.

Dewatering (Process Step 4): The clean slag will be dewatered using vibratory screens and stored in a bin or stockpile. Because slag is a glass-like material, dewatering is relatively easy and would continue when it is placed in storage piles. Dewatering of the char was not included as it is assumed that the char would be recycled to the gasifier in slurry form.

Table 39 provides the results of char separation tests conducted by Praxis on other slag samples for comparison with the TEC results. As may be seen, most slags had considerably higher (64-85%) recovery of clean slag compared to the TEC sample, which had 46.3% clean slag recovery. The low recovery for the TEC slag is attributed to the fact that the sample, which was obtained during the early stages of gasifier commissioning and start-up, contained an unusually high carbon content. The plant reported that the slag generated subsequently contains ~20% carbon. Therefore, in the subsequent analysis recovery of 70% char-free slag was assumed.

Table 39. Slag/Char Separation Results from Process Steps 1 & 2 for Various Slags

Slag	Feed		Clean Slag		Char		
	Wt%	Ash %	Wt%	Ash %	Wt%	Ash %	Carbon* %
Slag Sample 1	100	91.2	85.7	100.0	14.3	38.3	61.7
Slag Sample 2	100	84.9	70.0	99.4	30.0	51.1	48.9
Slag Sample 3	100	85.8	74.3	100.0	25.7	45.1	54.9
Slag Sample 4	100	83.7	73.1	99.3	26.9	41.0	59.0
TEC (Steps 1, 2, 3)	100	68.4	63.9	95.0	36.1	21.2	78.8
TEC (Steps 1, 2)	100	68.4	46.3	100.0	53.7	41.2	58.8

*Carbon content (determined by loss on ignition) would be 100% minus % Ash

2.5.2 Development of Conceptual Design for a Char Separation Facility

Tampa Electric Company's 250-MWe Polk Station IGCC facility uses a coal slurry feed consisting of Illinois No. 6 and Pittsburgh No. 8 coals which contain 10% ash and 2.5-3.6% sulfur. The facility uses approximately 2300 tons of coal per day on a dry basis. Clean slag target specifications of no more than 5% char were set by the plant to meet the requirements of a potential buyer. However, since no specifications were provided for the char product, we did not consider Step 3A which involves flotation. Upon completion of this subtask, TEC was to make a determination whether or not to include Praxis' design for a char separation process in its slag handling facility.